What can neutrino interactions on Carbon tell us about Argon?

Stephen Dolan
For the 3DST near detector group

With invaluable input from our theory collaborators:
G. Megias (U. Sevilla, IPMU), M. Barbaro (U. Torino), J. Caballero (U. Sevilla)

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Overview

- DUNE requires a %-level understanding of ν-N interactions
- 3DST would make an excellent detector for measuring ν-N interactions on Carbon
- The detector response will be well understood
  - (T2K's Super FGD will act as a prototype for 3DST)
- 3DST can also measure neutron kinematics
- **Key question:** *can precise measurements of neutrino interactions on Carbon help us understand those on Argon?*

The answer?

- **Key question:** *can precise measurements of neutrino interactions on Carbon help us understand those on Argon?*

- **No?**
  - We can barely describe ν-C scattering without heavy empirical tunes based on fudge factors rather than theory
  - Argon is a totally different nucleus, there's no guarantee our Carbon tunes will be useful at all
  - For DUNE we are better off using effective models from our ν-Ar ND data

The answer?

- **Key question:** *can precise measurements of neutrino interactions on Carbon help us understand those on Argon?*

- **Yes?**
  - Better nuclear models could well describe existing data and allow theory-driven corrections based on it
  - The nuclear physics of Carbon and Argon is the same, if we modify it based on Carbon data a good model would naturally allow its extension to Argon
  - Effective models are dangerous – if they can't describe Carbon and Argon, can they really describe the ND and FD E_ν spectra?

The answer?

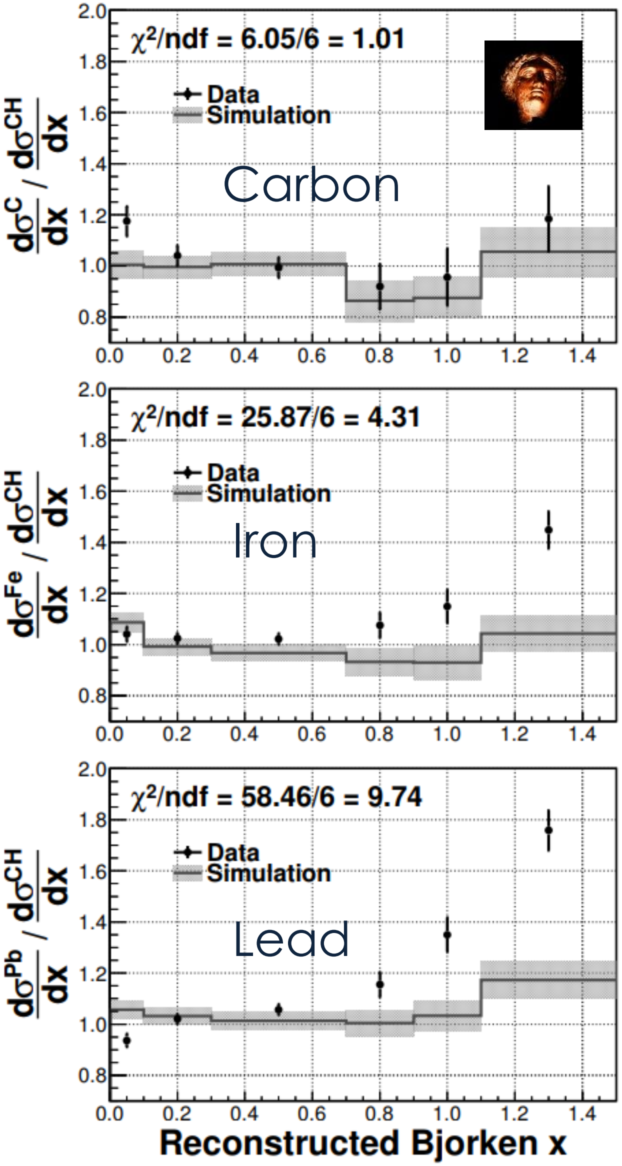
- **Key question:** *can precise measurements of neutrino interactions on Carbon help us understand those on Argon?*

- **Maybe?**
  - This is really a nuclear theory question: is it reasonable to expect a generator implementable nuclear model to describe Carbon and Argon data in exactly the same framework?
  - Best answer: ask theorists! We organised a small workshop on this.
  - The outcome: this technical note (will upload to DUNE DocDB very soon)
  - **This talk**: a very brief overview of our discussions

What do the generators say

$$x = \frac{Q^2}{2M_N\nu}$$

- The usual generators (GENIE, NEUT, NuWro) do not seem to well describe scattering on different nuclear targets …



Phys. Rev. Lett. **112**, 231801 (2014)

What do the generators say

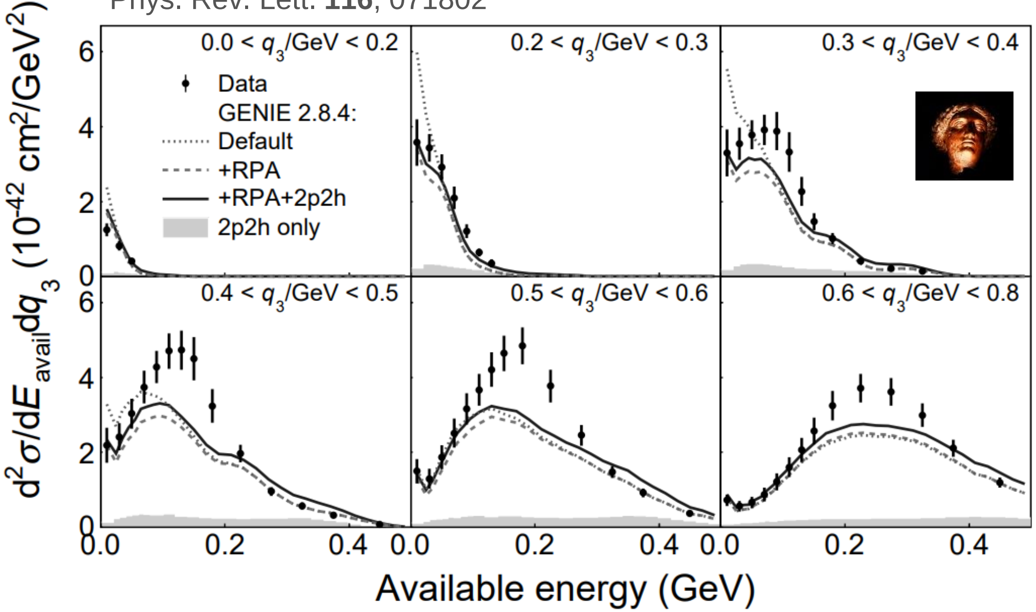
- The usual generators (GENIE, NEUT, NuWro) do not seem to well describe scattering on different nuclear targets …
- That said, they also can't describe (semi) exclusive interactions on Carbon …

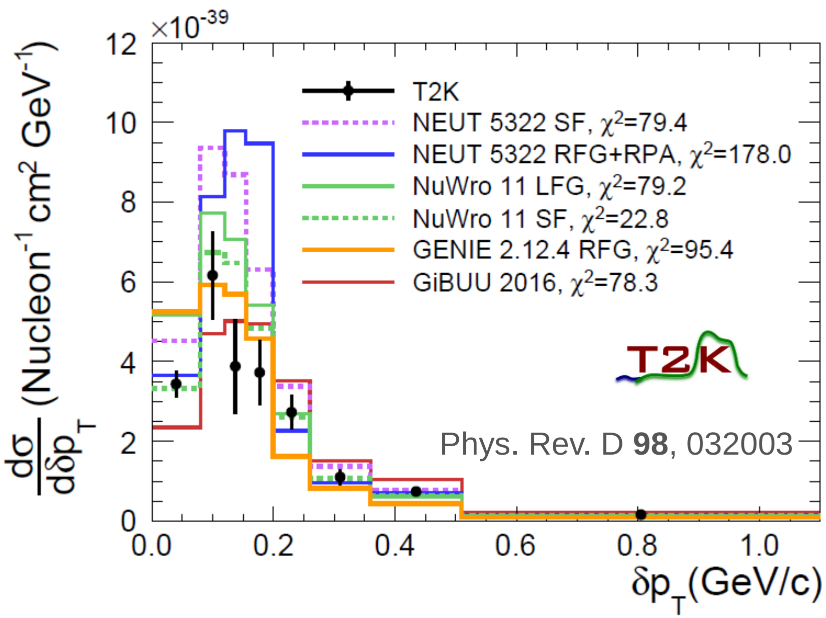
Inclusive: only measure the lepton

Exclusive: measure all particles

Semi exclusive: measure lepton and some hadrons

Phys. Rev. Lett. **116**, 071802





Phys. Rev. D **98**, 032003

What do the generators say

- The usual generators (GENIE, NEUT, NuWro) do not seem to well describe scattering on different nuclear targets …
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- … or inclusive scattering of electrons

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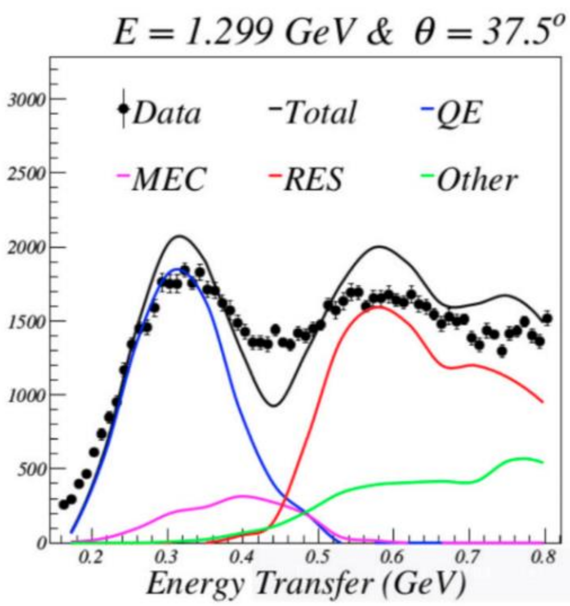
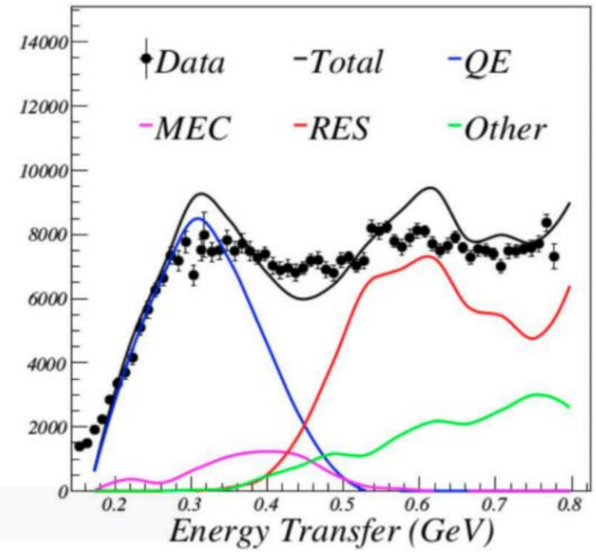
(Although even comparing to this data is an achievement – see the great work of the "e4nu" group, e.g. here)

^{12}C



^{56}Fe



*Genie R-2_12_10

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- Seems unlikely such models can reliably extrapolate between C and Ar with required precision for DUNE!

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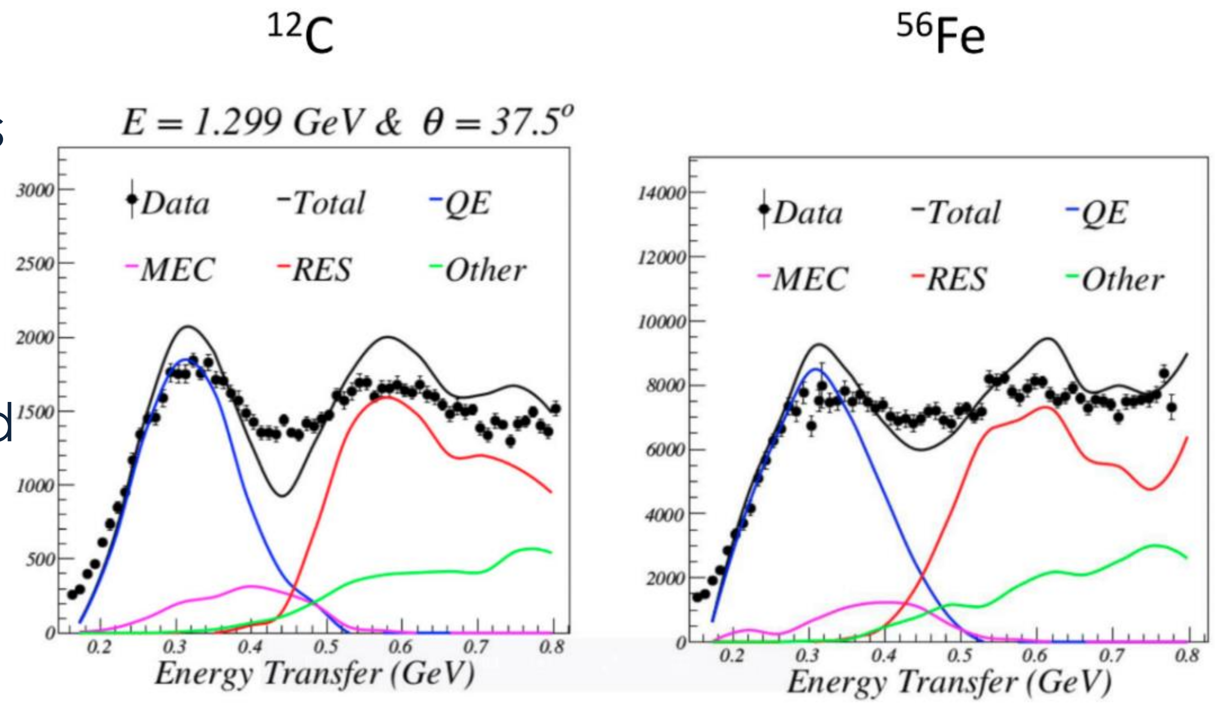

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- (… or between ND and FD)

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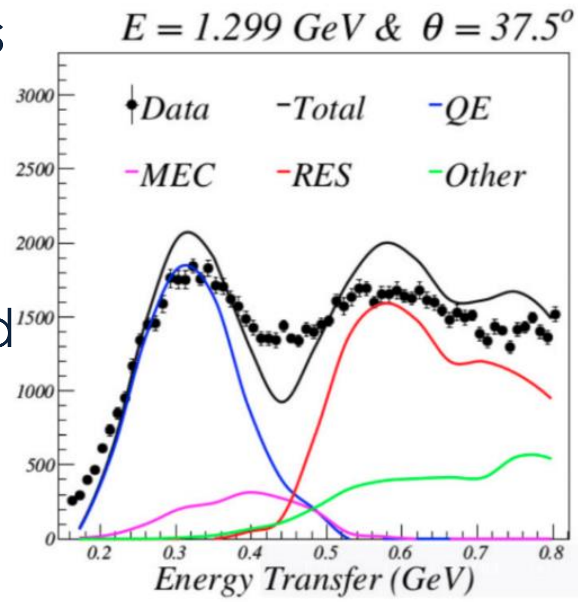

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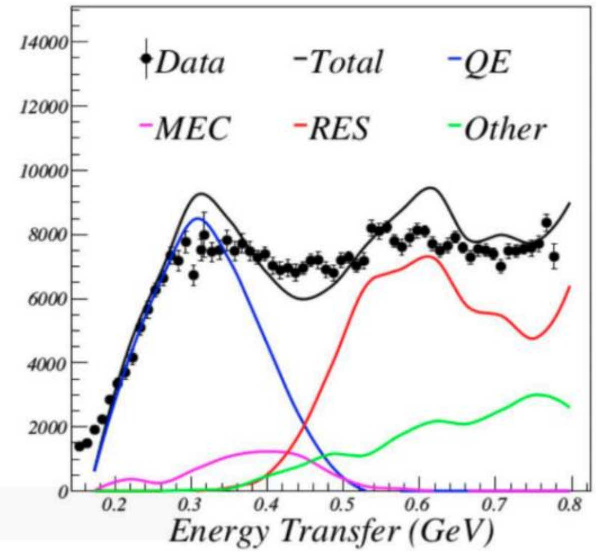
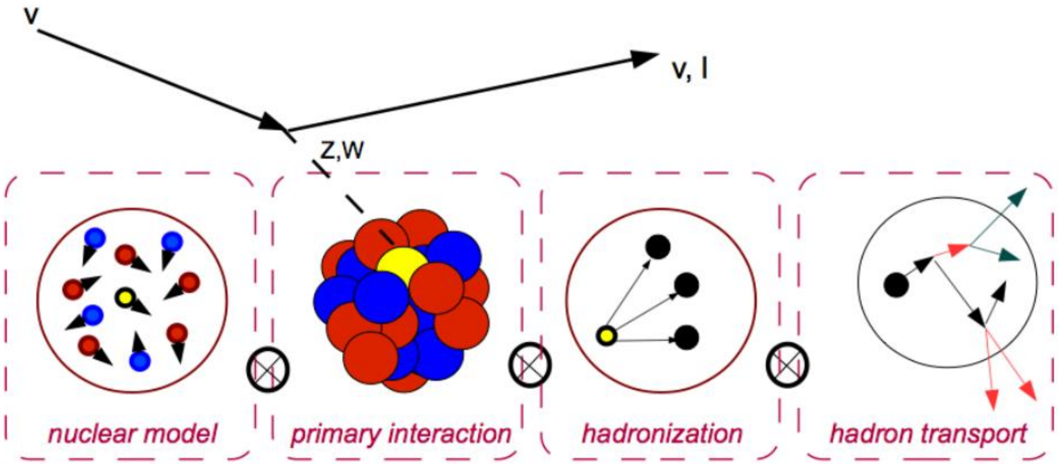


*Genie R-2_12_10

Phys. Rev. D **90**, 013014 (2014) arXiv:1905.08556

Why so bad?

- Most models in most generators a missing key ingredients …



This is often based on Fermi gas (local or global models)

Known to be overly simplistic, not suitable for exclusive scattering predictions

From Nieves' paper describing our best Fermi gas model (Phys. Rev. C **83**, 045501):

The LFG description of the nucleus has been shown to be well suited for inclusive processes and nuclear excitation energies of around 100 MeV or higher [1,37–42]. The reason is that in these circumstances one should sum up over several nuclear configurations, both in the discrete and in the continuum. This inclusive sum is almost insensitive to the details of the nuclear wave function,[5] in sharp contrast to what happens in the case of exclusive processes

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Phys. Rev. D **90**, 013014 (2014) arXiv:1905.08556

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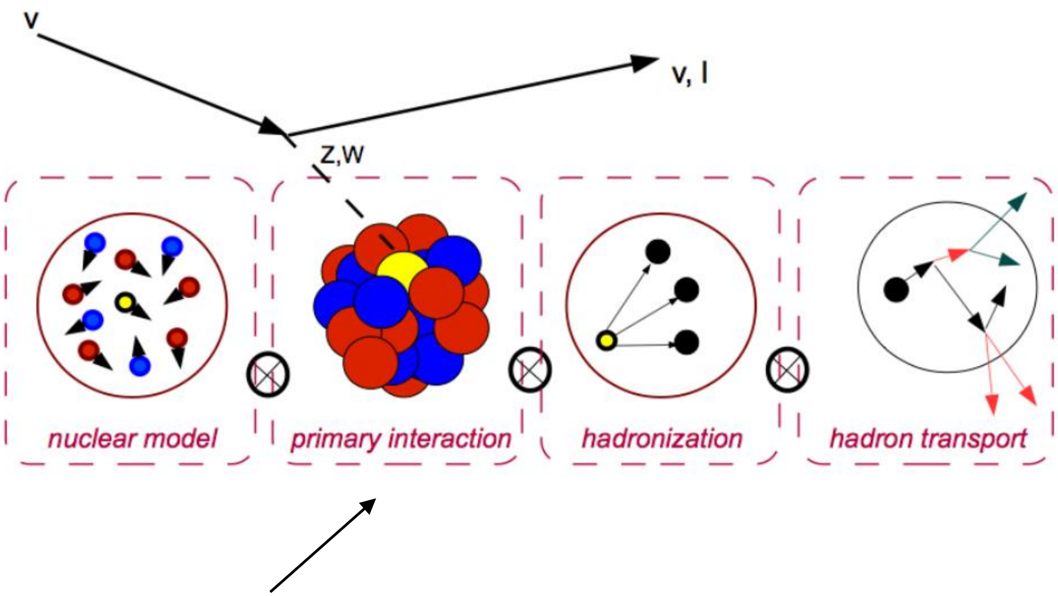

Asking for hadron kinematics, we need a *(semi)exclusive* input

- For CCQE interactions, something like: $\frac{d^6\sigma}{d\omega dq_3 dE_m d\boldsymbol{p_m}}$

But the theory input we use here is typically pre-integrated *inclusive* cross sections, giving us only the lepton kinematics

- Something like: $\frac{d^2\sigma}{d\omega dq_3}$ or maybe just $\frac{d\sigma}{dQ^2}$

Why so bad?

arXiv:1905.08556

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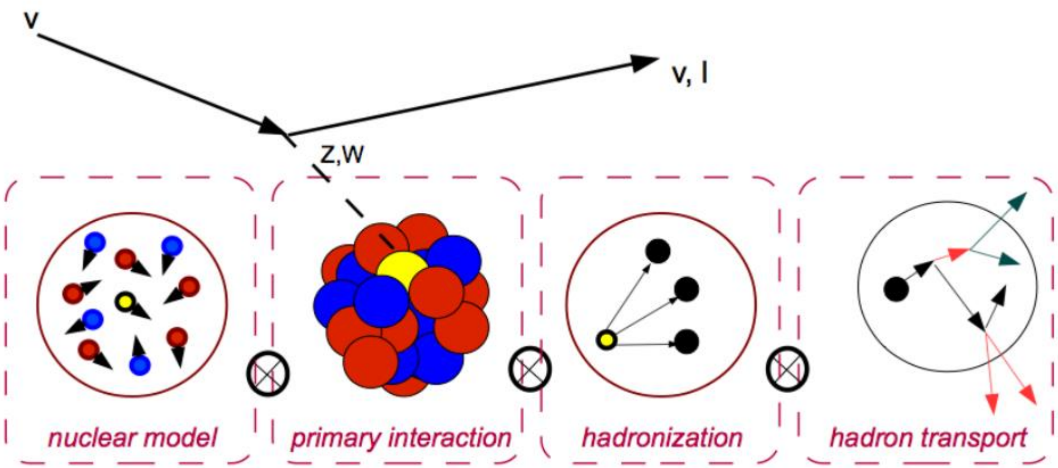
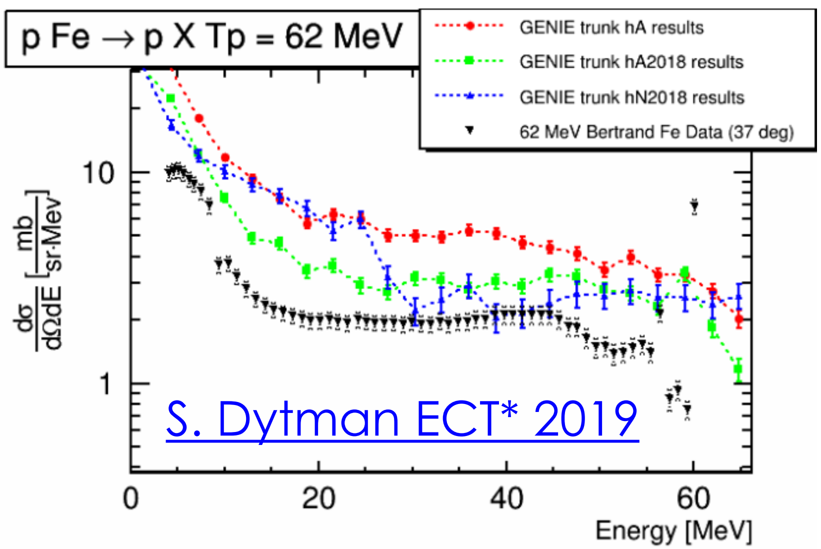




S. Dytman ECT* 2019

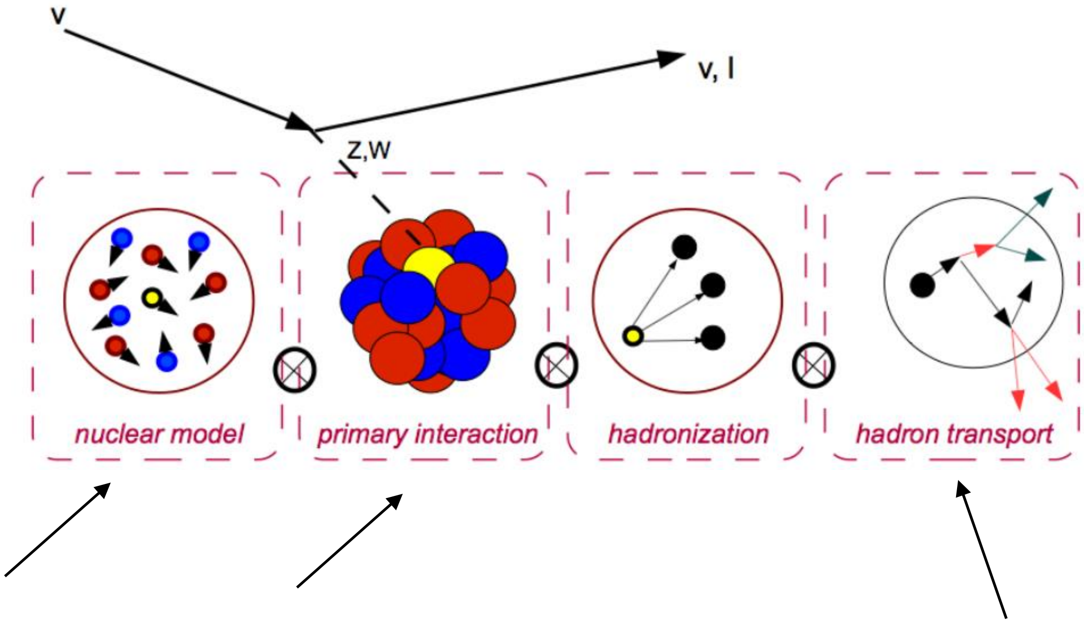
To describe FSI we usually use simple semi-classical cascade models.

These have been carefully tuned to hadron scattering data, but still struggle for some kinematics.

Why so bad?

arXiv:1905.08556

- Most models in most generators a missing key ingredients …



These different components are not linked (factorisation). E.g.:

- The nuclear potential in the FSI model is unrelated to the one in the nuclear model
- The primary interaction is often not affected by the nucleon sampled from the nuclear model

Can we do better?

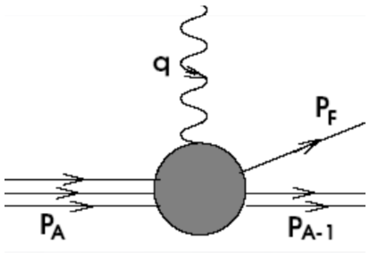
- With models like this 3DST would struggle to help improve an Argon model based on Carbon data.
  - If we change some part of the model based on Carbon data, there's no guarantee the change would help describe Argon
  - E.g. Carbon data might tell us we prefer an LFG to RFG on Carbon, but this might just be acting in lieu of a broken primary interaction model
- Important aside: with models like this can DUNE really expect to do a reliable near to far extrapolation with %-level constraints on neutrino interactions?
  - Probably not …
  - Independently of concerns about C→Ar extrapolation, it is imperative for DUNE that neutrino interaction modelling in event generators improves
- We need to do better! Can we?

RMF and SuSAv2

Phys. Rev. C **74**, 015502

Modern microscopic models can do better than what is currently in the generators. A good example is Relativistic Mean Field (RMF). It assumes:

- **Mean** field: nucleons in an average potential – independent of each other. Correlations go into the potential, but are not explicit.
- Impulse approximation



Basic idea: bound and scattered nucleons are solutions of a Dirac-like equation w/ **energy independent** real scaler (attractive) and vector (repulsive) potentials.

$$(\tilde{E}\gamma_0 - \vec{p}\cdot\vec{\gamma} - \tilde{M})\psi = 0$$

$$\tilde{E} = E - V(r)$$
$$\tilde{M} = M - S(r)$$

As the final state nucleon feels a potential its wavefunction is distorted, this is how RMF handles FSI

All nuclear targets are treated in the same way with the same tools

RMF and SuSAv2

Phys. Rev. C **90**, 035501
Phys. Rev. D **94**, 013012

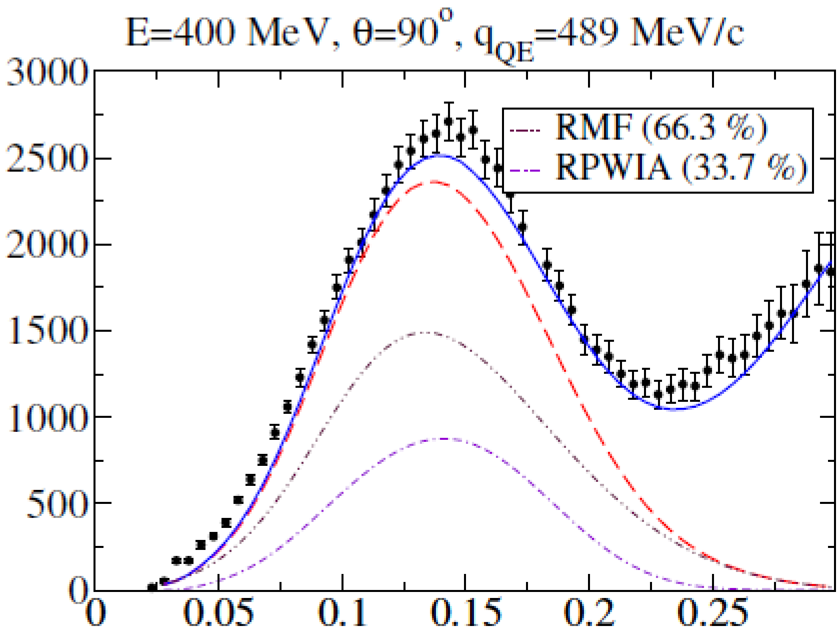
- RMF potentials are typically chosen to well describe the nuclear ground state (potentials directly from nuclear structure – no tuning to any data)

- RMF normally uses the same potentials for the initial and final state
  - But these are energy independent, so cannot work at all kinematics.
  - See problems at large q (FSI is too strong, should be very small).

- SuSAv2 solution: introduce a kinematic dependent **blending function** between RMF and RPWIA (no FSI in final state)
  [RPWIA = Relativistic Plane Wave Impulse Approximation]

- Blending function built from carbon (e,e') data (A-dependence of the blending function is expected to be very weak)

- The blending function is an effective modification of the nuclear potential at large q. Work is in progress to apply the same modification directly in RMF ("ED-RMF")



G. D. Megias PhD Thesis

Scaling behaviour

- RMF is also capable of describing a fundamental property of inclusive ℓ-N scattering: scaling

- It has been observed that in electron scattering experiments that QE interactions can be written as:

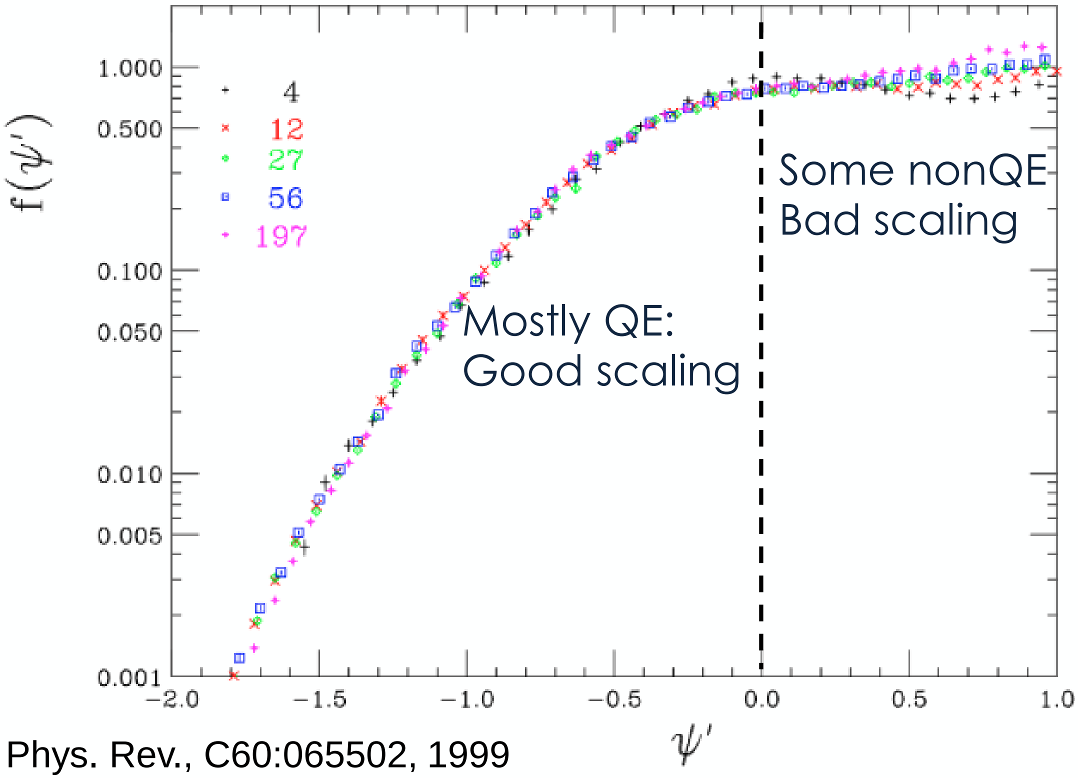
$$\sigma_{QE} = \frac{f(\psi')}{k_F}\sigma_{single\,nucleon}$$

- So all the nuclear dynamics is the scaling function:

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})}$$

Scaling behaviour

- Experimentally it has been found that this scaling function is mostly independent on the nuclear target for inclusive QE
- A model struggling to predict scaling data indicates a problem



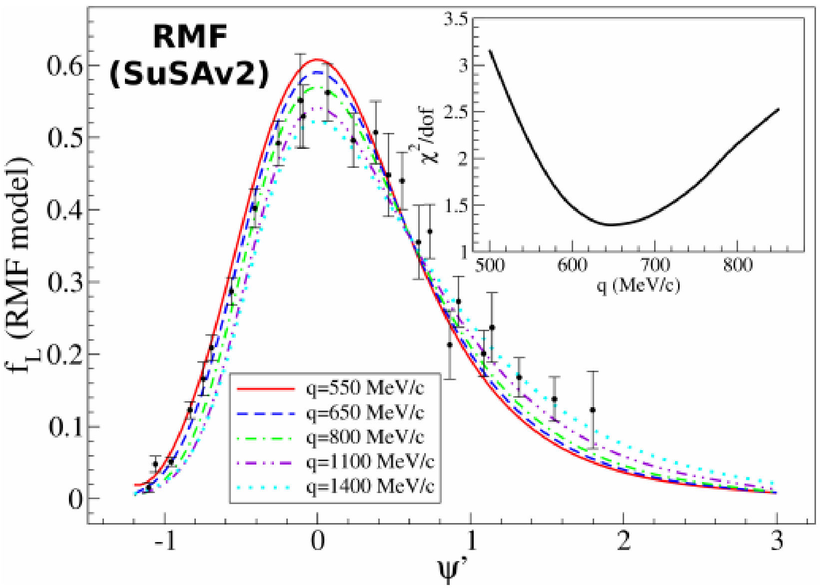
Phys. Rev., C60:065502, 1999

- If a model scales well, we automatically can extrapolate **inclusive** predictions from one nuclei to another
- Could validate a scaling function on Carbon and have confidence that it extends to Argon (for the inclusive case)

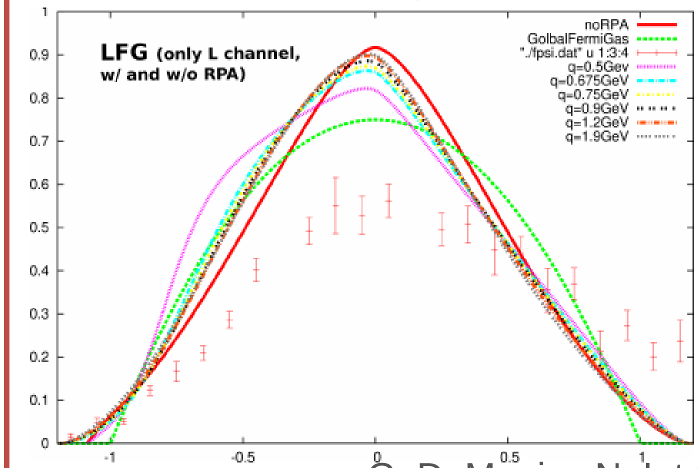
Scaling behaviour

- With all their missing ingredients, the models in the generators generally fail to describe the shape of the scaling function …
- On the other hand, RMF does well

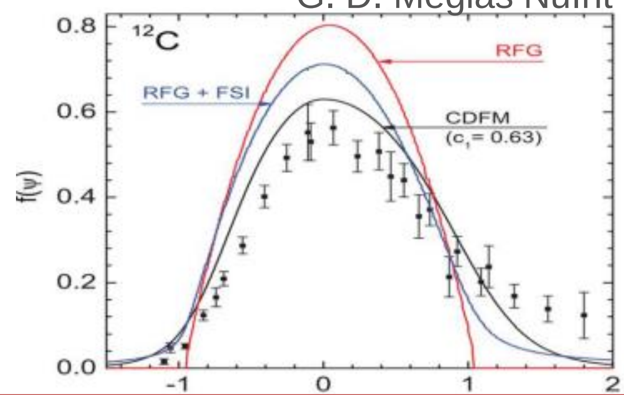
RMF Phys. Rev. C **90**, 035501



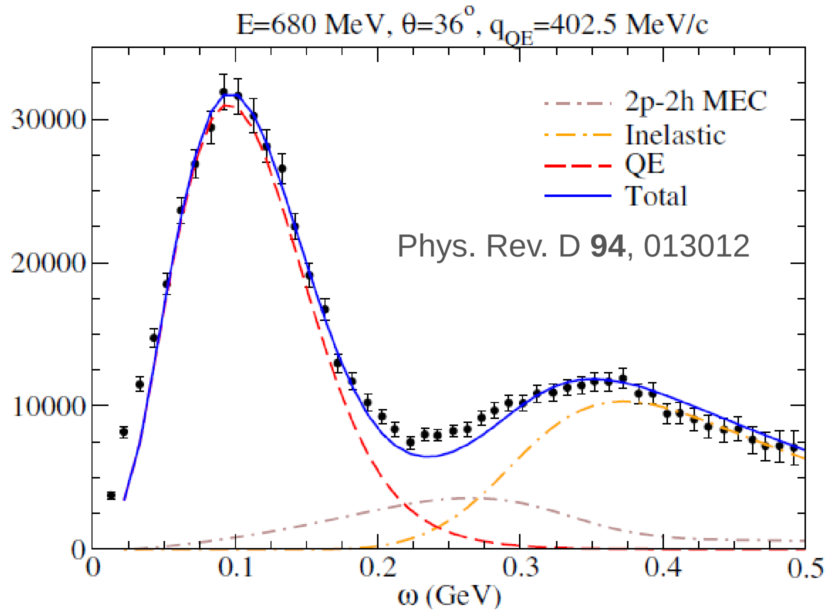
Models in the generators



G. D. Megias NuInt 18

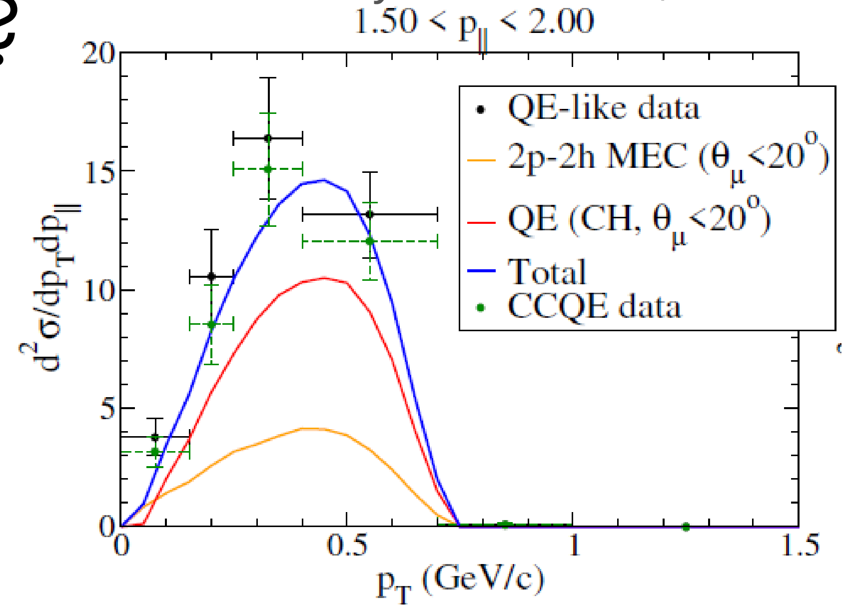


Does it work (Carbon)?

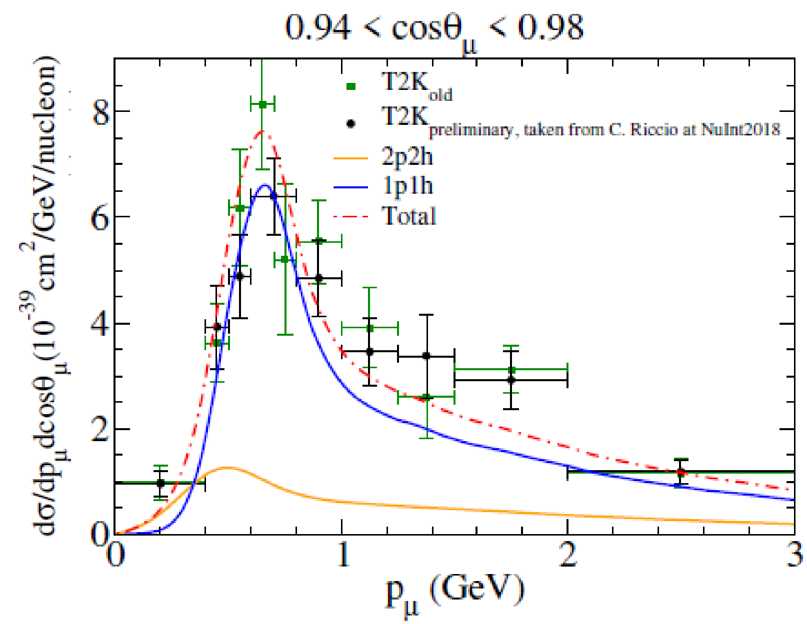


- Based on sound microscopic model calculations
- **Well validated on electron scattering data**
- Is able to describe neutrino scattering data

Phys. Rev. D **99**, 113002

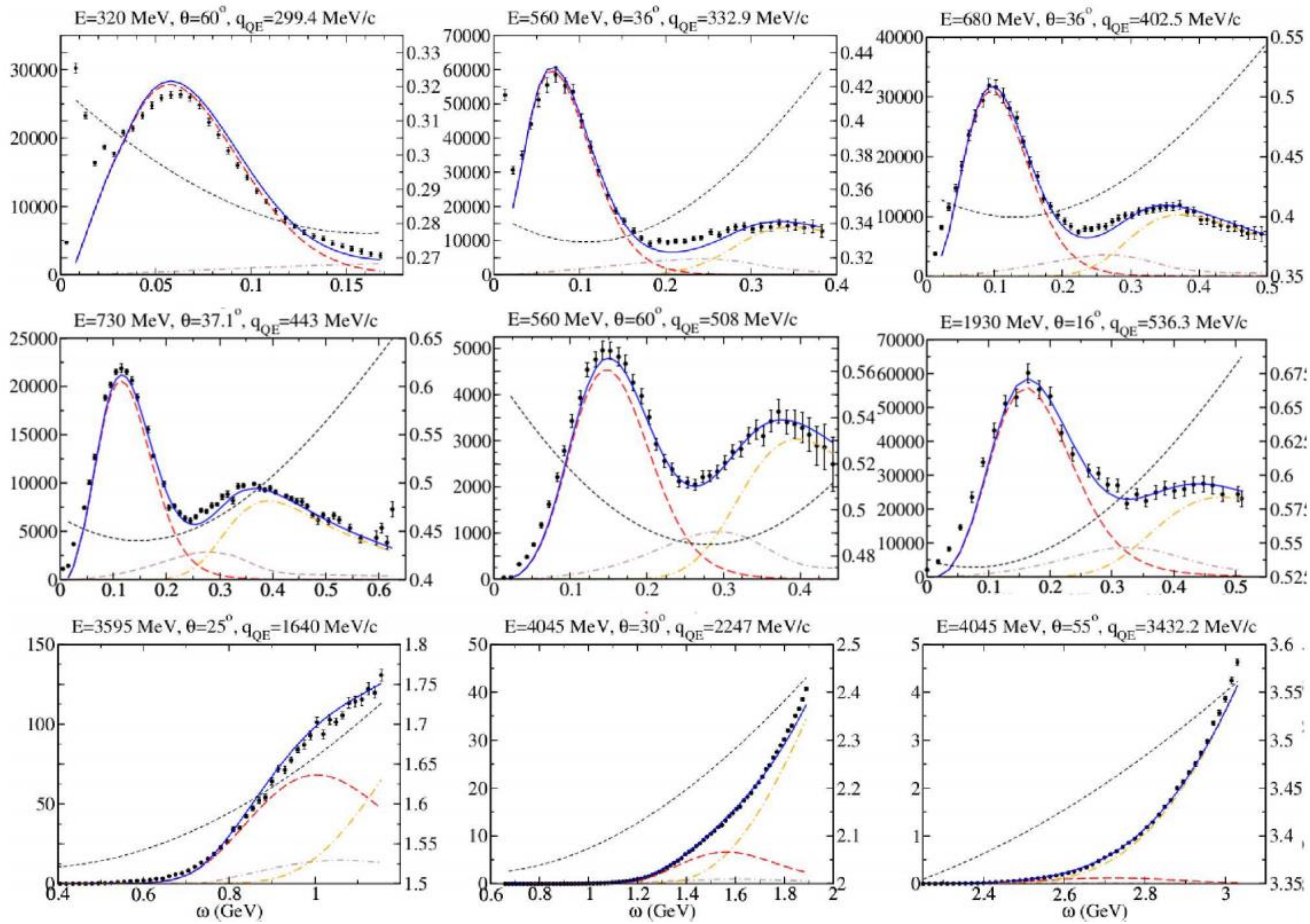


arXiv:1905.08556



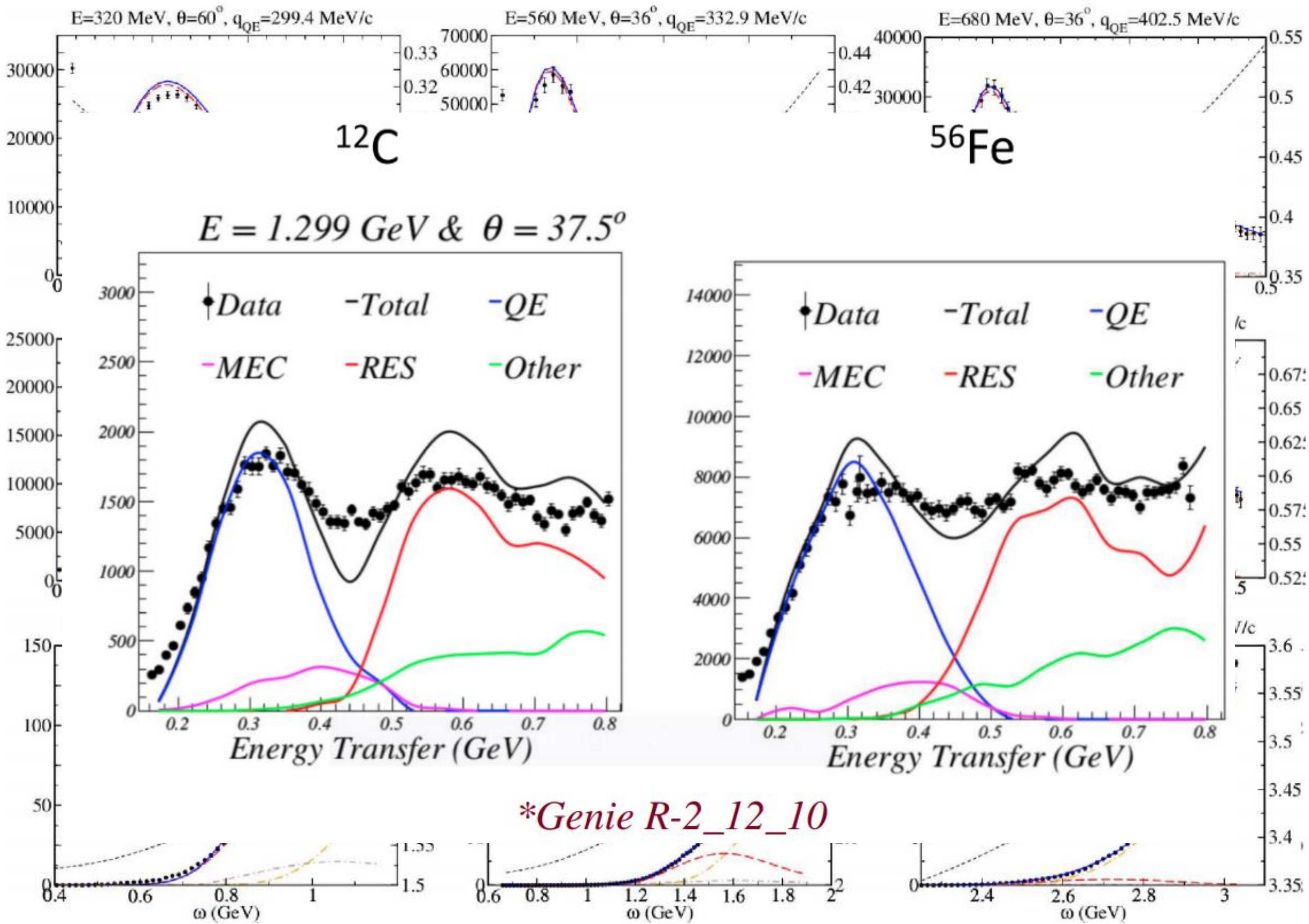
Does it work (Carbon)?

Phys. Rev. D **94**, 013012



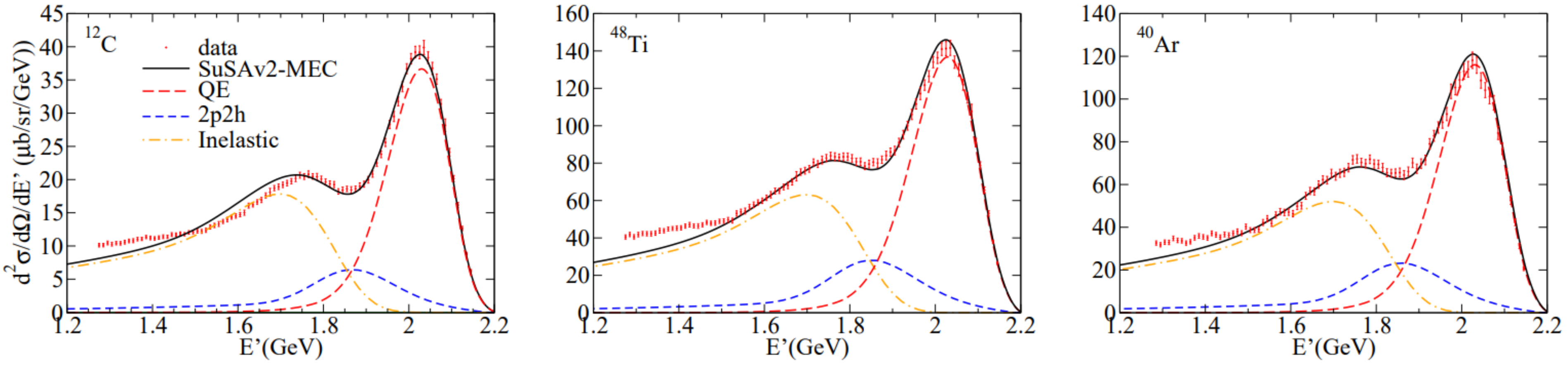
Does it work (Carbon)?

Phys. Rev. D **94**, 013012



Does it work (Argon)?

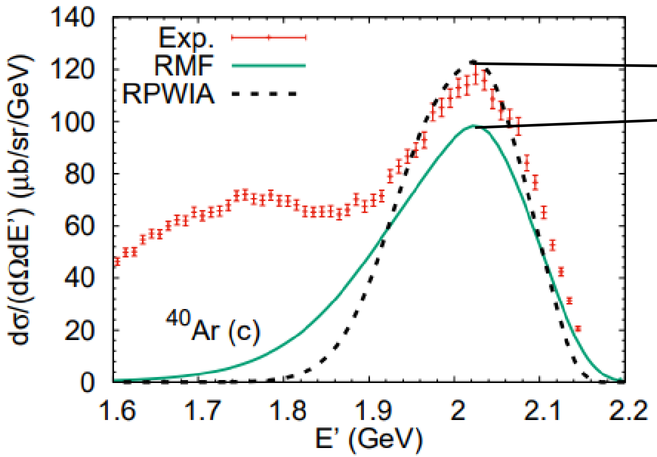
Phys. Rev. C **99**, 042501(R)

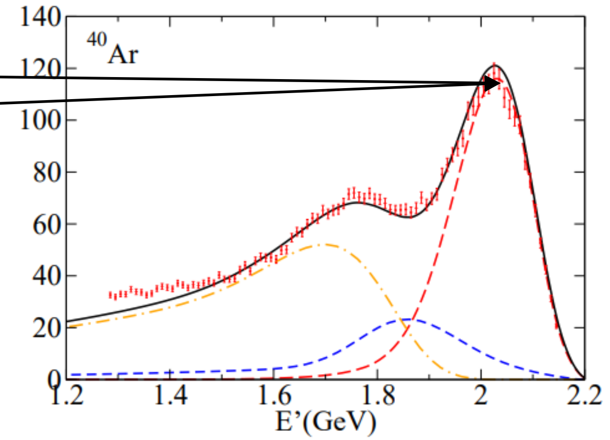


- Excellent agreement in QE and 2p2h region

Does it work (Argon)?

Phys. Rev. C **99**, 042501(R)



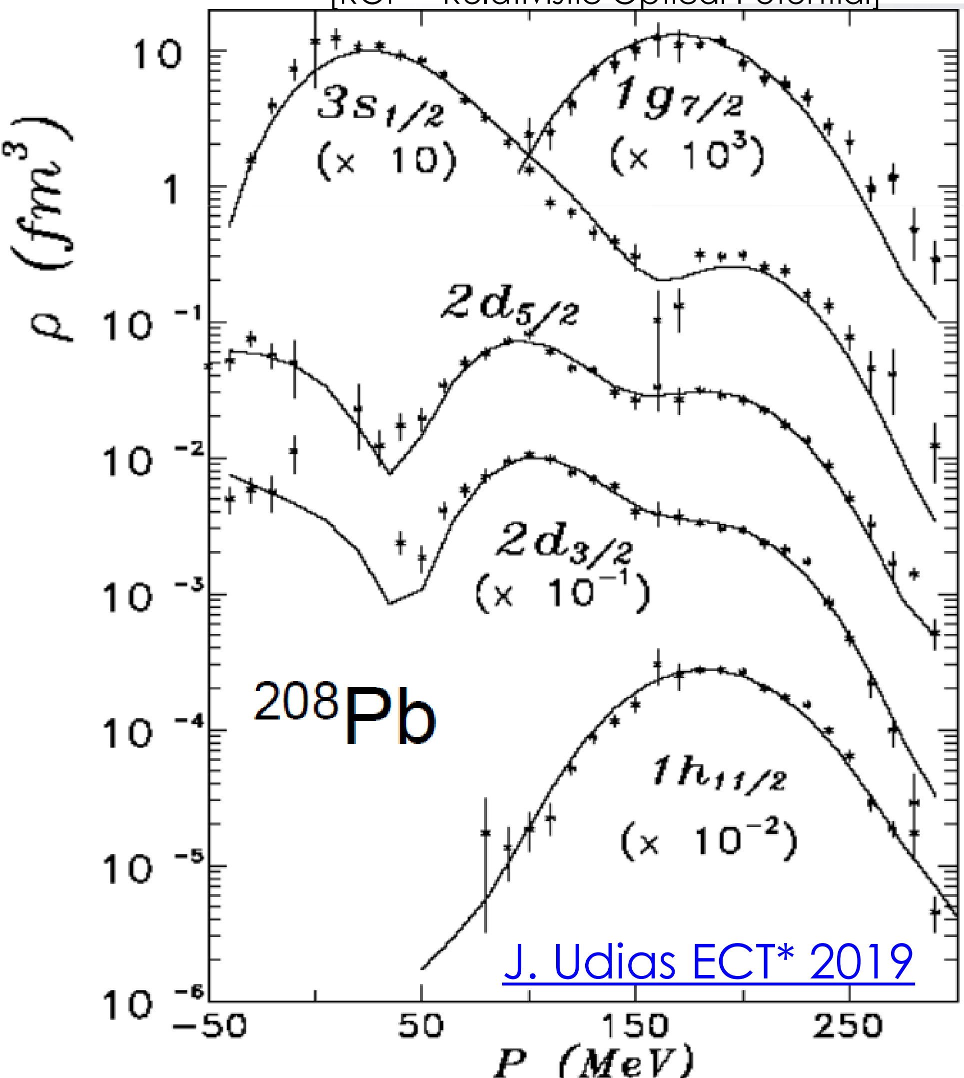


- Excellent agreement in QE and 2p2h region
- **RMF-RPWIA blending is essential to match the data**
  - This was a model modification based on carbon data, then extrapolated to Argon (and Titanium)
  - *An example of how a real microscopic model can help us learn about Argon from Carbon data*

Does it work (exclusive)?

RMF+ROP

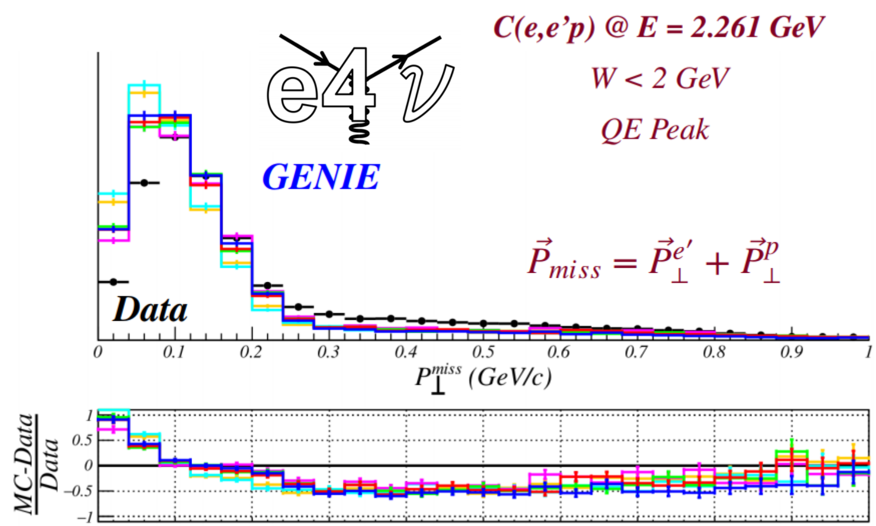
[ROP = Relativistic Optical Potential]



JM Udias et al., PRC48, 2731 (1993), PRC51 3246 (1995)

Generators (GENIE)

- RMF is able to reproduce exclusive data sensitive to detailed nuclear structure!



Summary

- Current models in the generators do not have much predictive power in extrapolating from Carbon to Argon
  - If we tune to Carbon, there is no guarantee this helps Argon

Summary

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  - If we tune to Carbon, there is no guarantee this helps Argon
- This is not the case for modern models such as RMF
  - Treat Argon and Carbon using the same tools: fix some aspect of the nuclear dynamics on Carbon, it should be reflected in Argon
  - E.g. SuSAv2 weakened FSI in RMF based on Carbon data and found Argon predictions needed the same modification

Summary

- Current models in the generators do not have much predictive power in extrapolating from Carbon to Argon
  - If we tune to Carbon, there is no guarantee this helps Argon
- This is not the case for modern models such as RMF
  - Treat Argon and Carbon using the same tools: fix some aspect of the nuclear dynamics on Carbon, it should be reflected in Argon
  - E.g. SuSAv2 weakened FSI in RMF based on Carbon data and found Argon predictions needed the same modification
- If we can implement such models in the event generators, then 3DST would be able to provide direct and relevant constraints on the nuclear effects most important for DUNE
  - Using a well understood detector that can measure neutron kinematics
  - In Argon, nuclear effects are more convoluted: difficult to disentangle. Carbon is much more simple.
  - Carbon also offers a "lever-arm" compared to Argon to offer an additional handle on nuclear effects (e.g. can't enhance M_A^{QE} to fill in for 2p2h on Carbon and Argon simultaneously)

The future?

Input from and collaboration with theorists is fundamental to overcoming these challenges

- Experiments have outstripped the over simplified models in generators.

NuInt 18 Experimental summary talk – K. McFarland

With every topic we find that the challenges can be met only with the active support and collaboration among specialists in strong interactions and electroweak physics that include theorists and experimentalists from both the nuclear and high energy physics communities.

NuSTEC White Paper (Prog.Part.Nucl.Phys. 100 (2018) 1-68)

- Apart from rigorous work, inspiration (and whining abilities ☺) (especially young) theorists need institutional support!

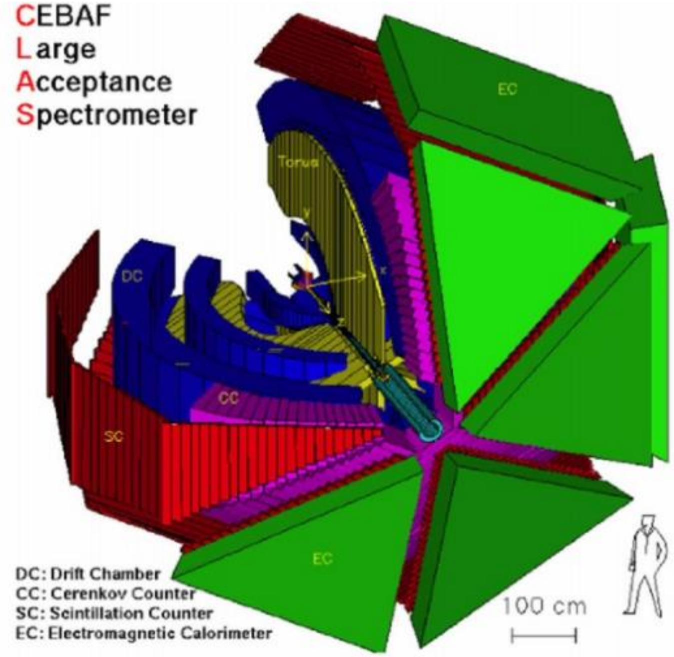
NuInt 18 Theoretical summary talk – V. Pandey

NEUTRINO 2018 cross-section talk - U. Mosel

- Precision era of neutrino physics requires more sophisticated generators and a dedicated joint effort in nuclear theory and generator development
- This joint effort has to be funded as integral part of experiments

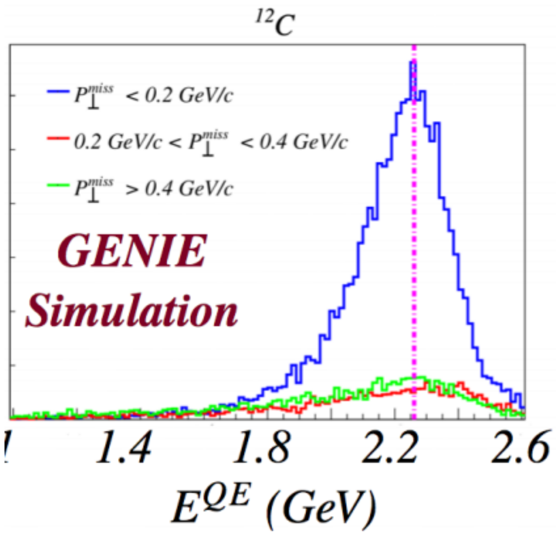
Backups

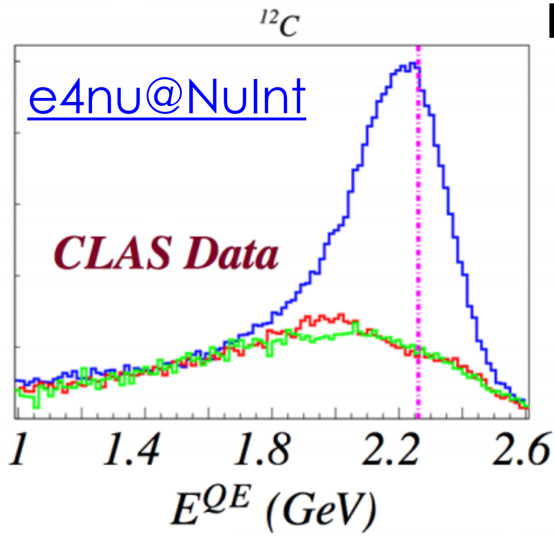
It's getting better – e4nu



- Generators are becoming more able to make neutrino and electron scattering predictions in the same framework

- New data from CLAS (e-scatting): specifically to help better understand neutrino scattering



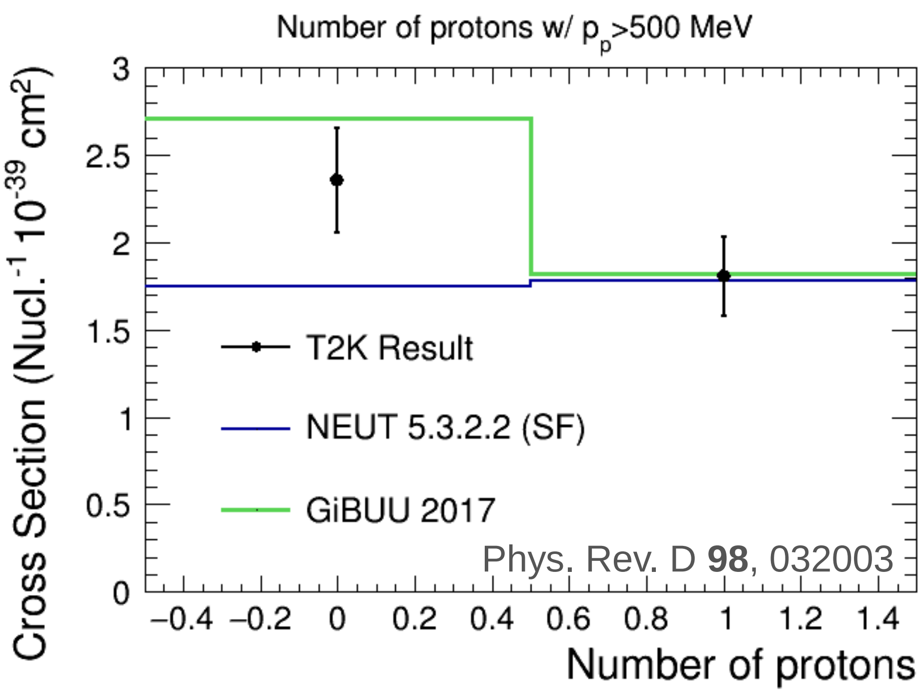


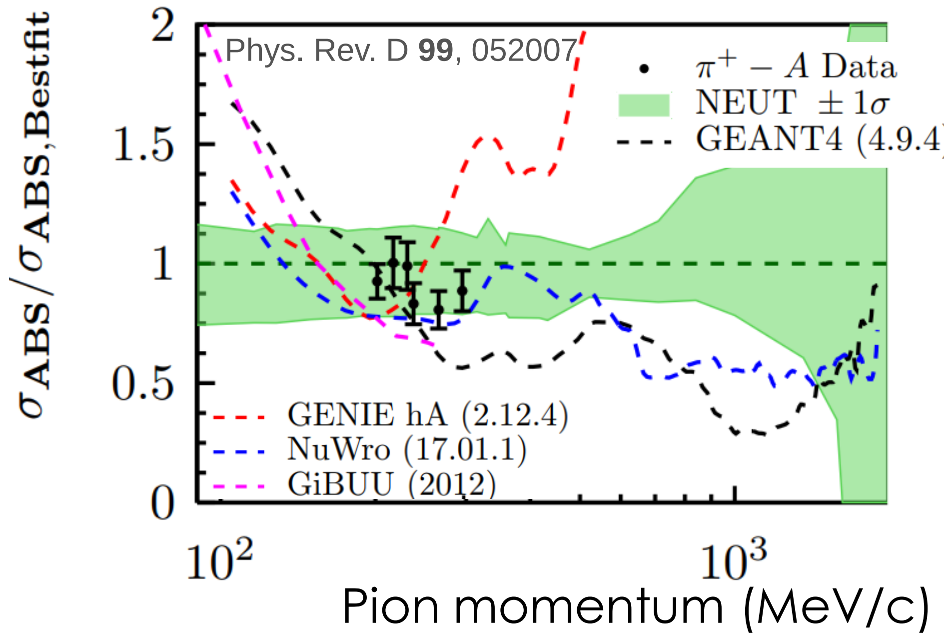
Example:

- In CLAS we know $E_{e,inital}$
- But can still reconstruct it as if it was a neutrino
- See how well generators predict this
- Almost a direct test of bias in neutrino scattering

Still trouble – FSI modelling

- Typically use semi-classical cascades to describe effects of FSI on the outgoing hadrons
- **Exception**: GiBUU uses a more sophisticated transport theory
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Quite different predictions for pion and nucleon FSI – improved understanding is crucial





The axial part scales too

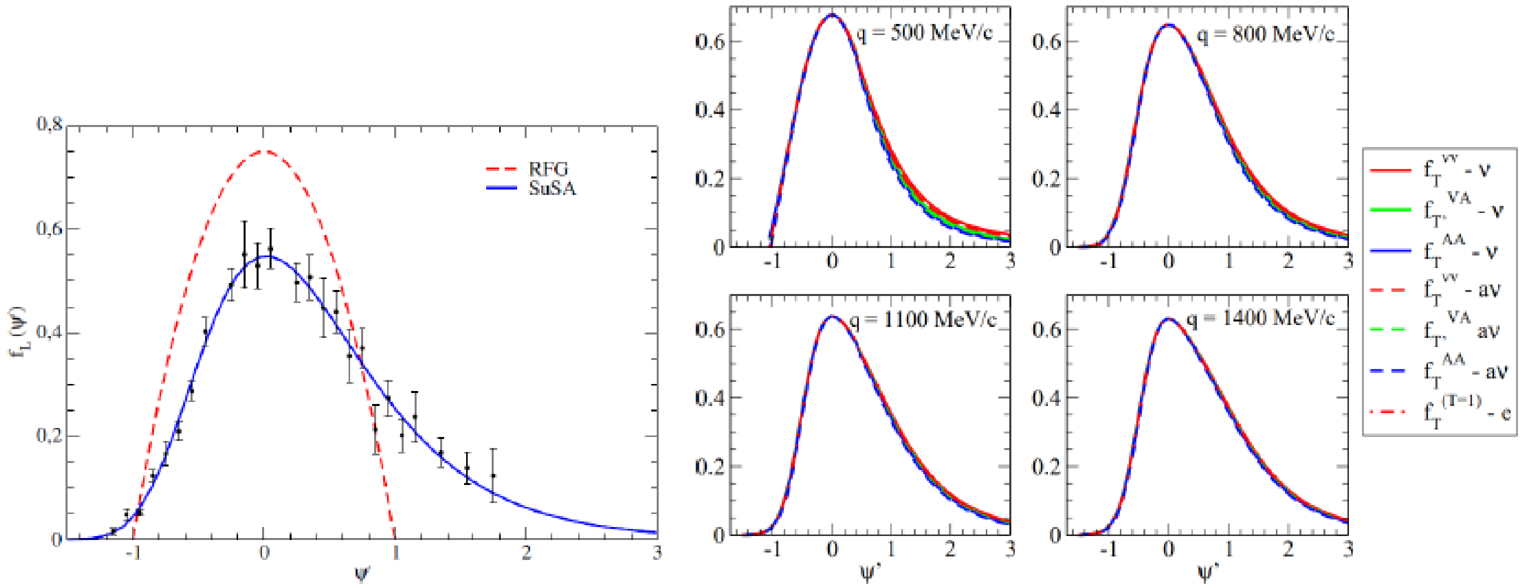


Figure 2: Both plots show the scaling function as a function of the scaling variable ($f(\Psi')$), as is also shown in Fig. 1. These plots are taken from references [9; 11]. The left shows that a Relativistic Fermi Gas (RFG) model is completely unable to describe the scaling function extracted from data (whilst RMF can, as shown in Fig. 1). The right plot shows that RMF predicts that the scaling behaviour of the vector (VV), axial (AA) and vector-axial (VA) contributions to neutrino-nucleus scattering and the scaling behaviour of electron scattering are all the same (see Ref. [9] for further details).

e,e'p on Oxygen from RMF+ROP

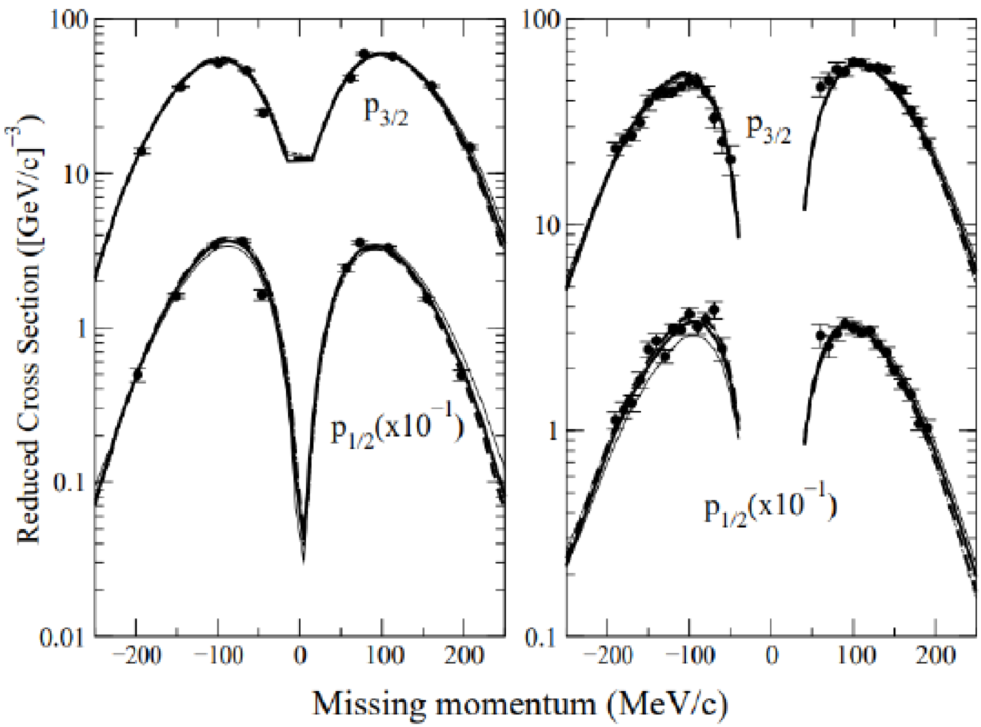
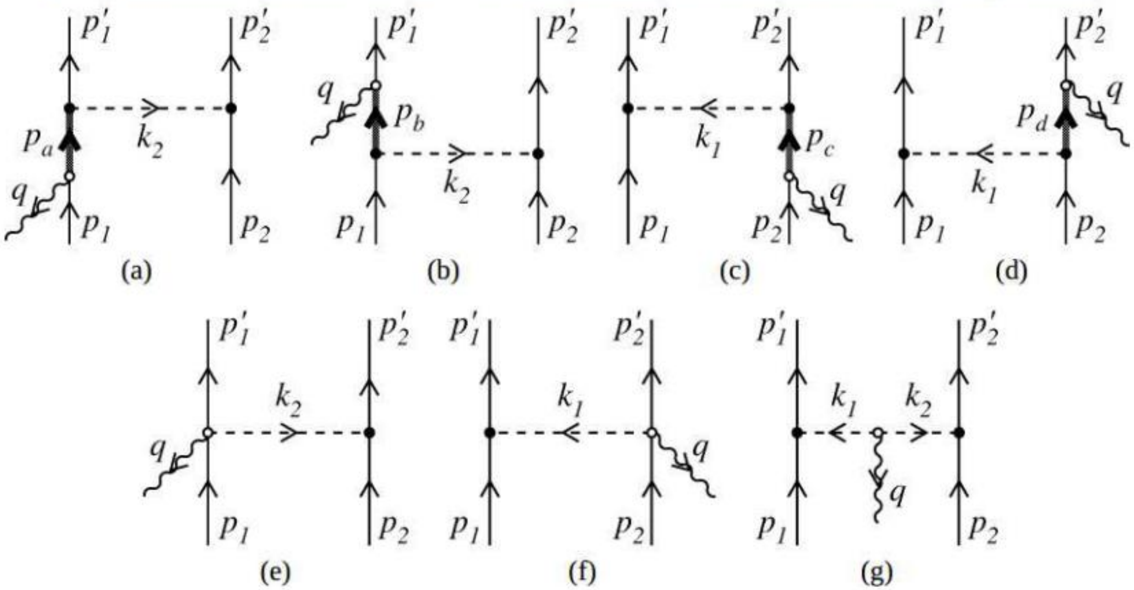


Figure 5: A comparison of RMF, using ROP for ejected nucleons, model predictions to missing momentum measurements from exclusive electron scattering data on an Oxygen target, separated by nuclear shell. This figure is taken from reference [13]. The two sides of the figure correspond to comparisons to two different data sets. Although only Oxygen is shown here, RMF is also capable of describing similar data from a range of heavier targets, including Lead.

SuSAv2 2p2h

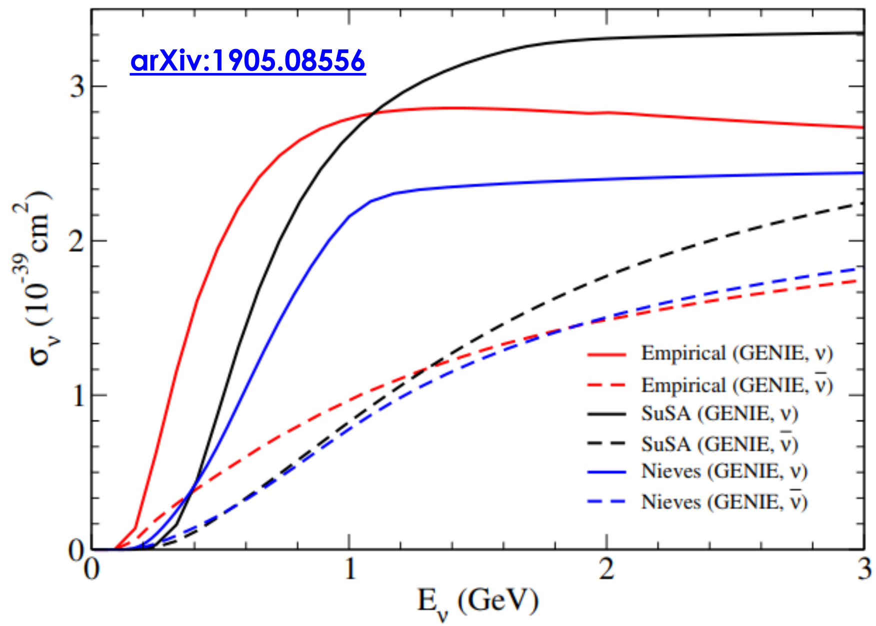
$$W^{\mu\nu}_{2p-2h} = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3h_1 d^3h_2 \frac{M^4}{E_1E_2E'_1E'_2}\Theta(p'_1,p'_2,h_1,h_2)$$
$$r^{\mu\nu}(\mathbf{p}'_1,\mathbf{p}'_2,\mathbf{h}_1,\mathbf{h}_2)\delta(E'_1+E'_2-E_1-E_2-\omega)\,,$$

Over 100,000 terms are involved in the calculation, with seven-dimensional integrations



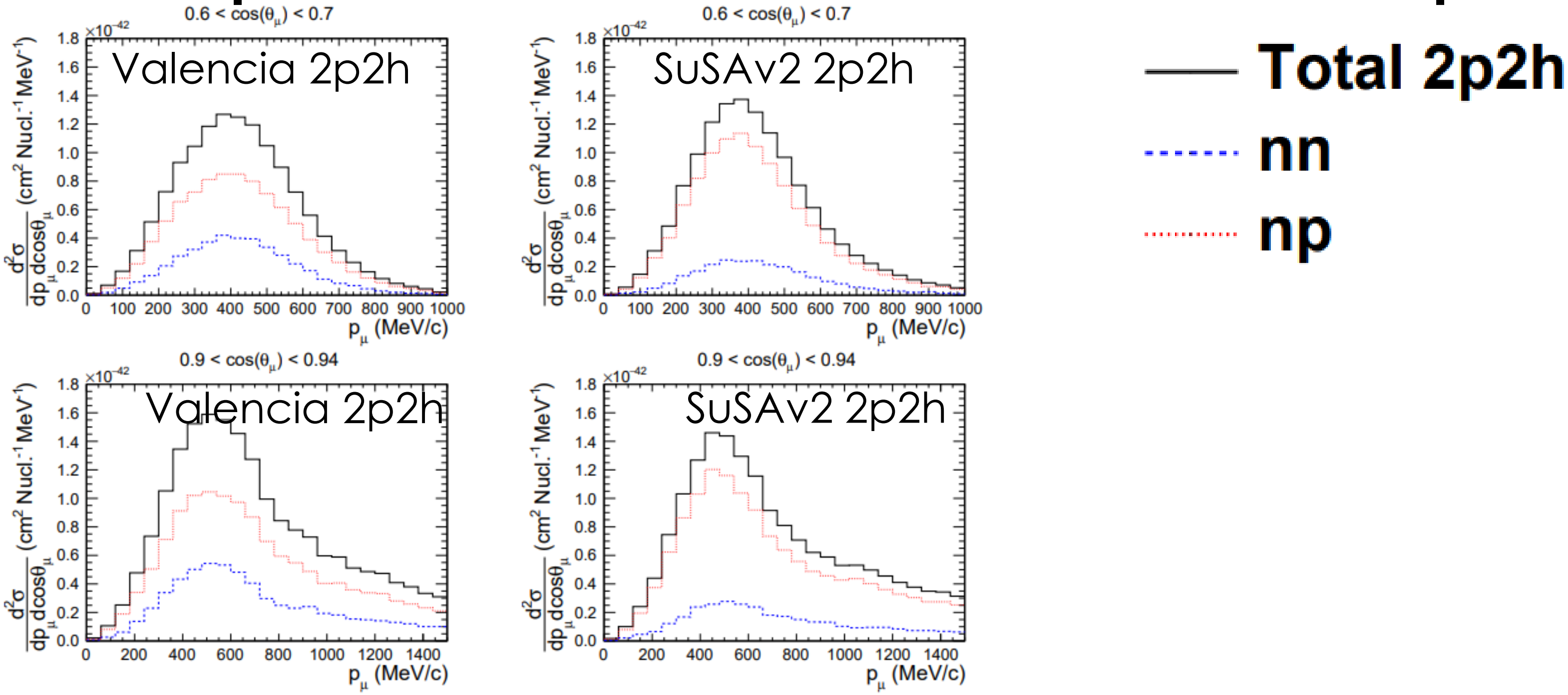
- Based on the calculation performed by De Pace et al., (2003) for (e, e') scattering and extended to the weak sector by Amaro, Ruiz Simo et al.
  [PRD 90, 033012 (2014); PRD 90, 053010 (2014); JPG 44, 065105 (2017); PLB 762, 124 (2016)]
- Performed within an RFG nuclear model (like Nieves), SuSAv2-MEC is fully relativistic – no approximations
- HUGE calculation, takes a long time to calculate a full cross section
  - Normally a parameterisation is used

Comparison to Valencia 2p2h



- Valencia model makes some non-relativistic approximations limiting validity above 1.2 GeV, SuSAv2-MEC does not.

Comparison to Valencia 2p2h

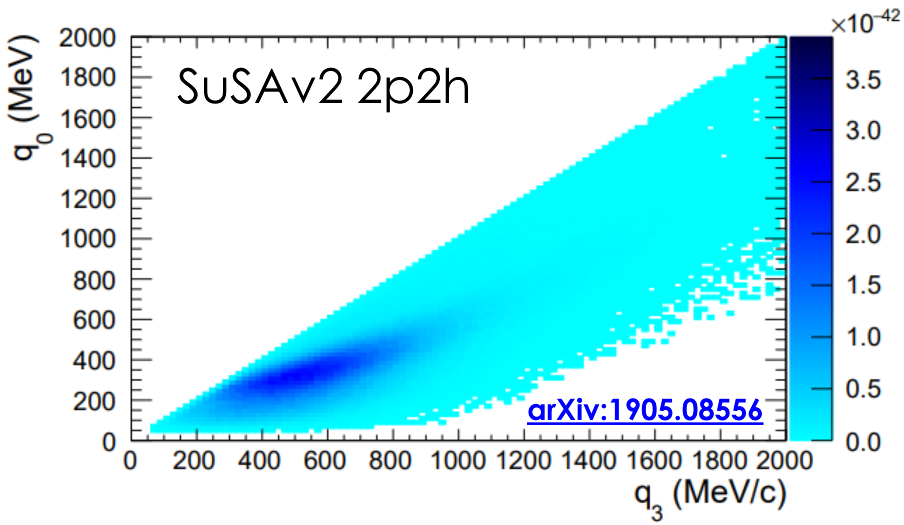


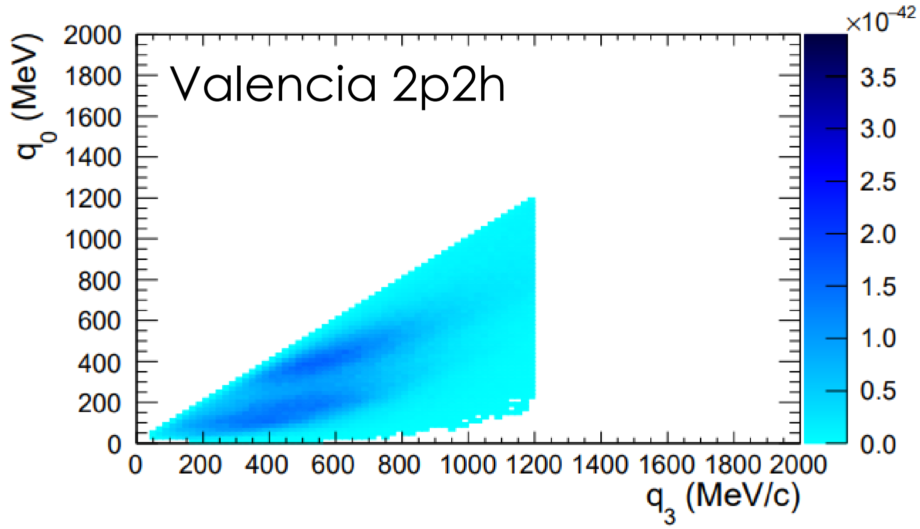
- Valencia model makes some non-relativistic approximations limiting validity above 1.2 GeV, SuSAv2-MEC does not.

- Valencia model rejects direct/exchange interference terms, SuSAv2-MEC does not – Valencia predicts relatively less pp final states

10.1016/j.physletb.2016.09.021

Comparison to Valencia 2p2h





- Valencia model makes some non-relativistic approximations limiting validity above 1.2 GeV, SuSAv2-MEC does not.
- Valencia model rejects direct/exchange interference terms, SuSAv2-MEC does not – Valencia predicts relatively less pp final states
- Valencia model includes a different set of diagrams (some from imaginary part of the W)

SuSA 1p1h: Scaling

Basic idea: use the scaling function encode nuclear dynamics

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \longrightarrow f(\psi') = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)_{exp}}{\sigma_{Mott}(v_L G_L^{ee'} + v_T G_T^{ee'})}$$

In inclusive QE scattering we can observe:

- ☆ Scaling of 1^{st} kind (independence on q)
- ☆ Scaling of 2^{nd} kind (independence on Z)

$\Longrightarrow$ **SuperScaling**

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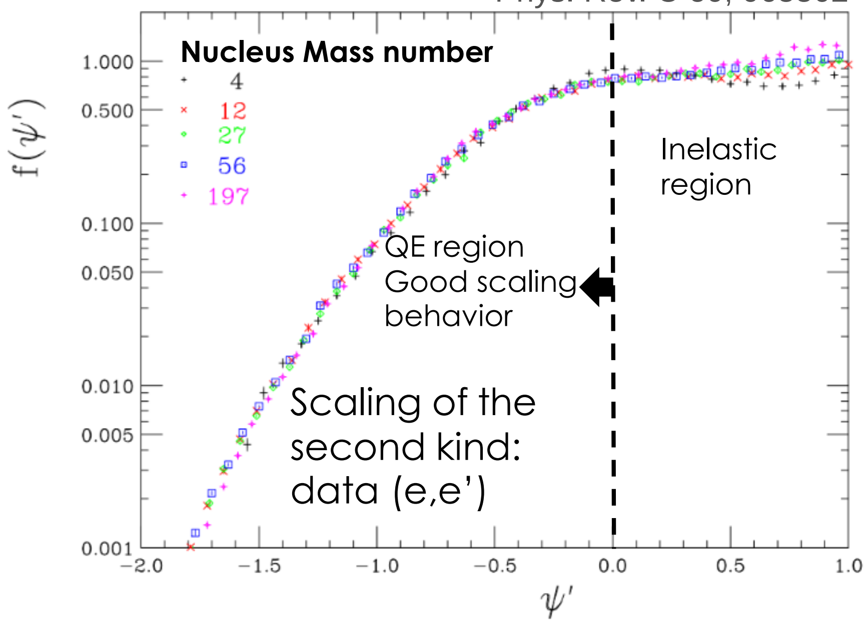

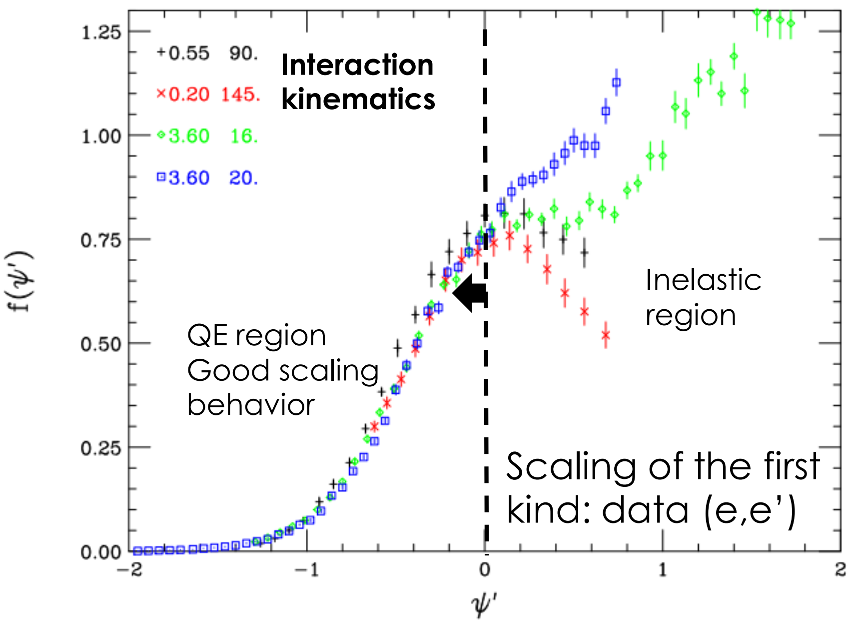

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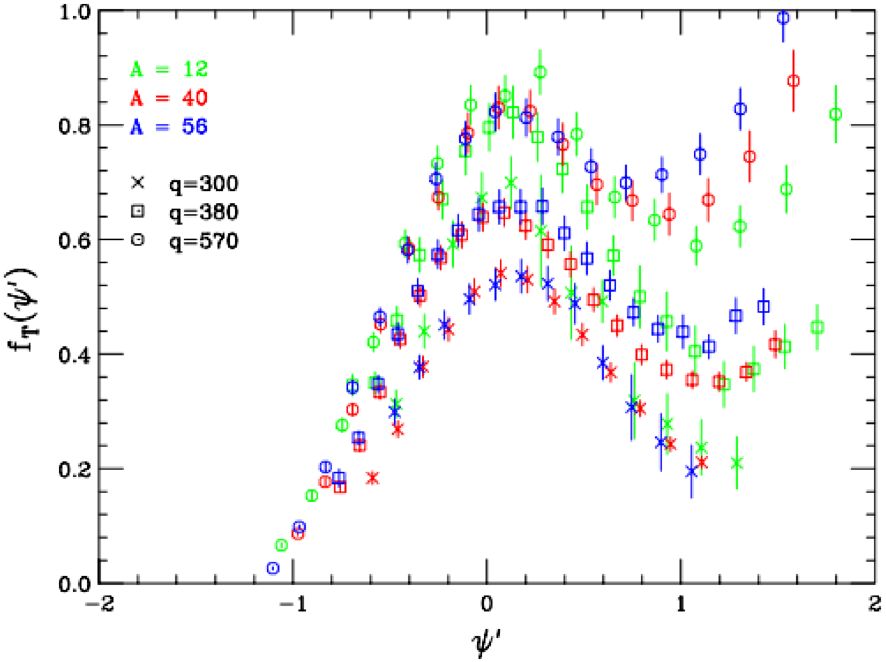
Can only extract scaling function from data for longitudinal channel: transverse has too much non-QE (which does not super-scale)



SuSA (v1): assume transverse and longitudinal scaling functions are the same and extract from data

Not quite right: evidence that $f_T > f_L$ by 15%-20%

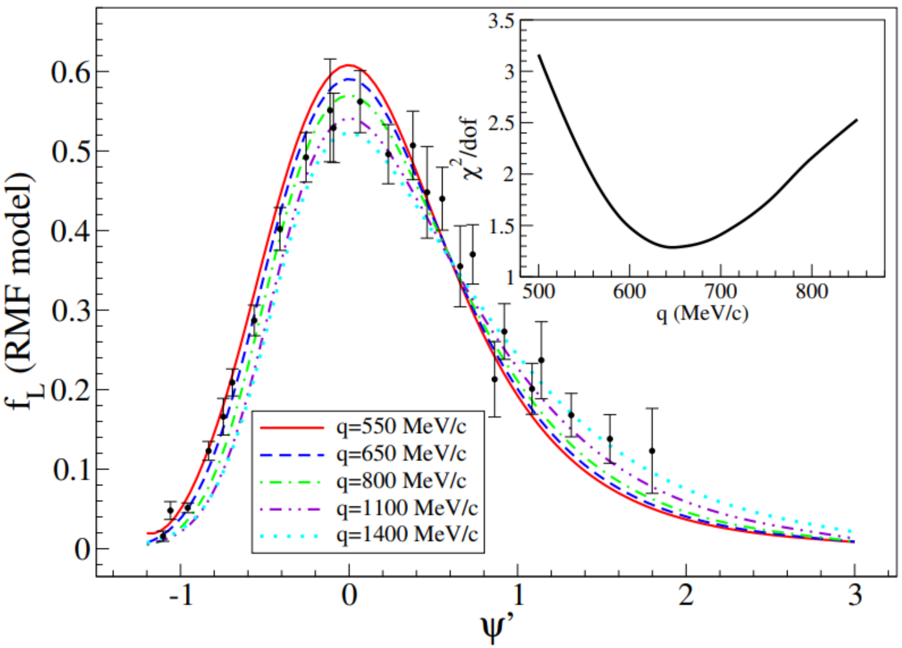
Enter SuSAv2!

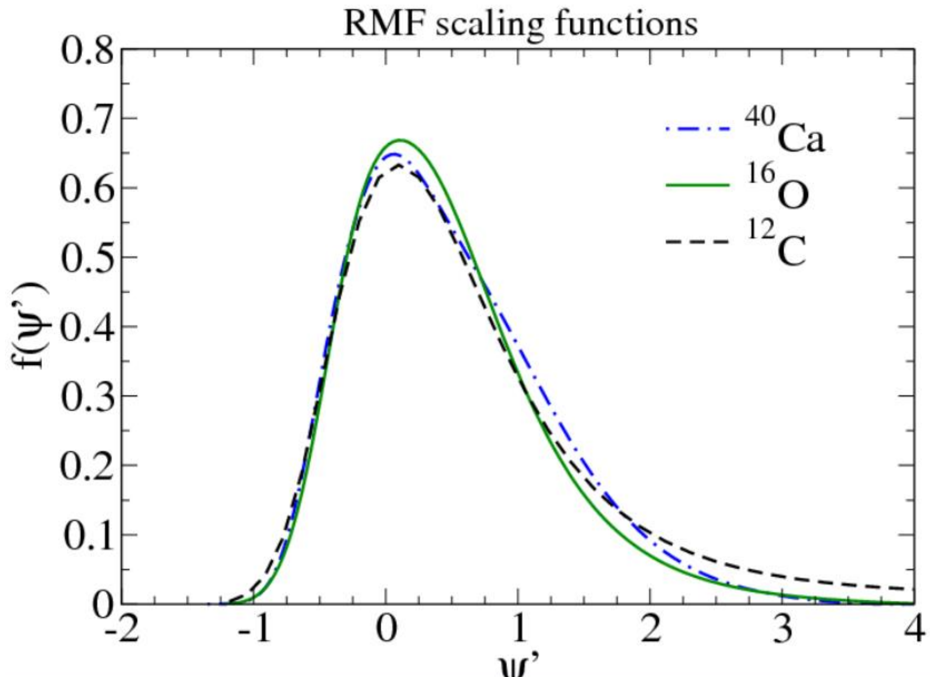
SuSAv2 1p1h: use of RMF

Basic idea: use the scaling function encode nuclear dynamics

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \longrightarrow f(\psi') = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)_{exp}}{\sigma_{Mott}(v_L G_L^{ee'} + v_T G_T^{ee'})}$$

Construct separate T and L scaling functions from microscopic model: Relativistic Mean Field (RMF) …





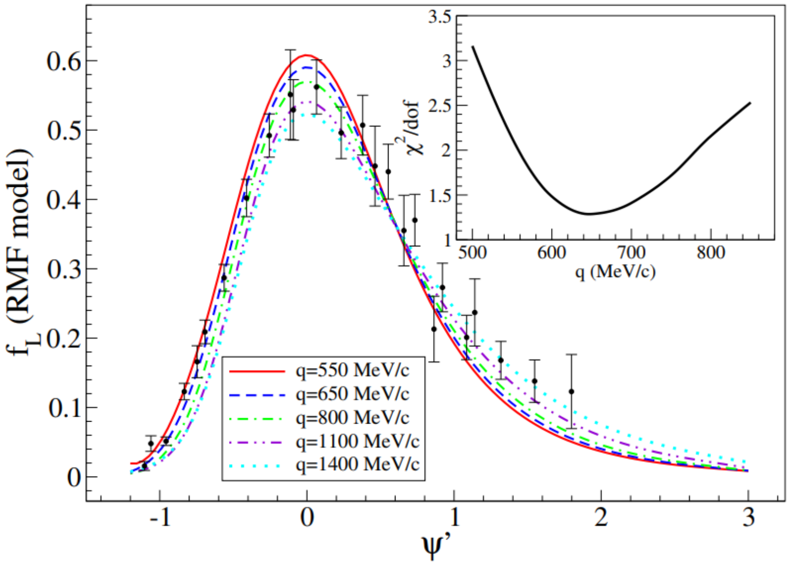
SuSAv2

Basic idea: use the scaling function encode nuclear dynamics

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \longrightarrow f(\psi') = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)_{exp}}{\sigma_{Mott}(v_L G_L^{ee'} + v_T G_T^{ee'})}$$

Construct separate T and L scaling functions from microscopic model: Relativistic Mean Field (RMF)

RMF FSI too strong at large q: blend to RPWIA.



SuSAv2

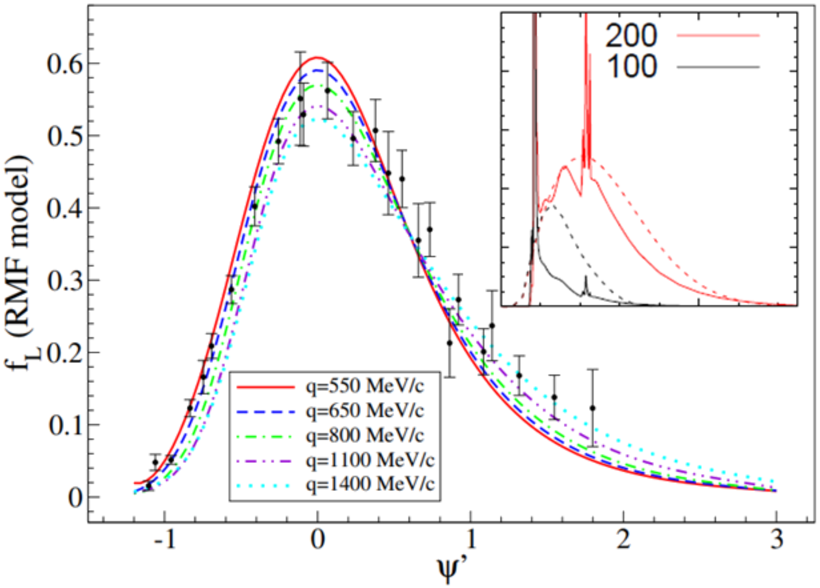
Basic idea: use the scaling function encode nuclear dynamics

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \longrightarrow f(\psi') = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)_{exp}}{\sigma_{Mott}(v_L G_L^{ee'} + v_T G_T^{ee'})}$$

Construct separate T and L scaling functions from microscopic model: Relativistic Mean Field (RMF)

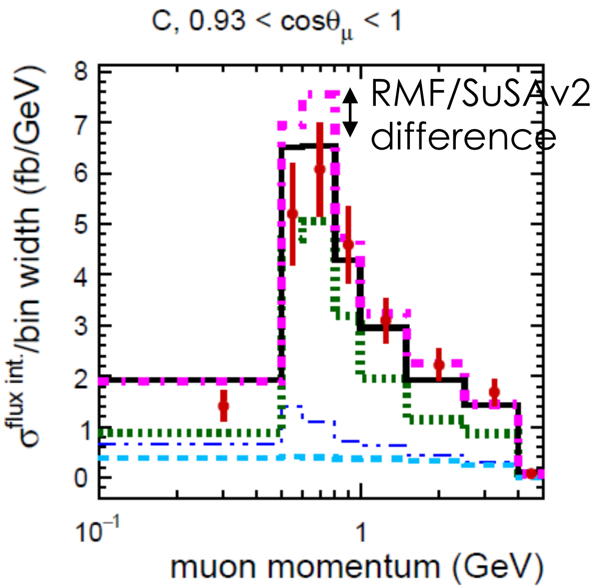
RMF FSI too strong at large q: blend to RPWIA.

Caveat: RMF slightly violates scaling of the first kind at low kinematics



Expect significant variations between SuSAv2 and RMF for small ω, q_3

Future SuSA (v3?) will address this



Next steps

- Clearly exclusive predictions need work – but this needs exclusive input from theory …
  - Thankfully exclusive (ν, ℓ', N') ED-RMF is coming soon (also for pions)!

Two options:

- Directly implement 5D RMF cross section
  - Most complete implementation, but slow
  - Maybe could find ways to remove/parameterise some dimensions / responses …

- If we use PWIA (not RPWIA) the cross section factorises as in SF formalisms:

$$\frac{d^6\sigma}{\mathrm{d}\omega d\boldsymbol{q} dE_m d\boldsymbol{p}_m} = KS(E_m, \boldsymbol{p}_m)\mathrm{L}_{\mu\nu}\mathrm{H}^{\mu\nu}\delta(\omega + M - E_m - E_{p'})$$

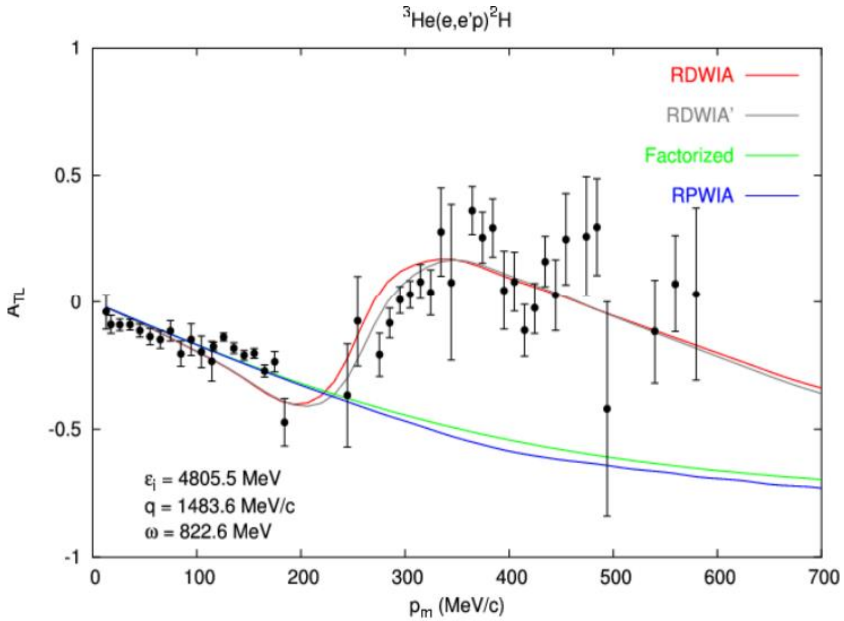
  - Then we need a 5D single nucleon hadron tensor, $H^{\mu\nu}$, (or maybe a boost to COM …) and the RMF spectral function, $S(E_m, \boldsymbol{p}_m)$.
  - Much easier, but how much do we loose in this factorisation?

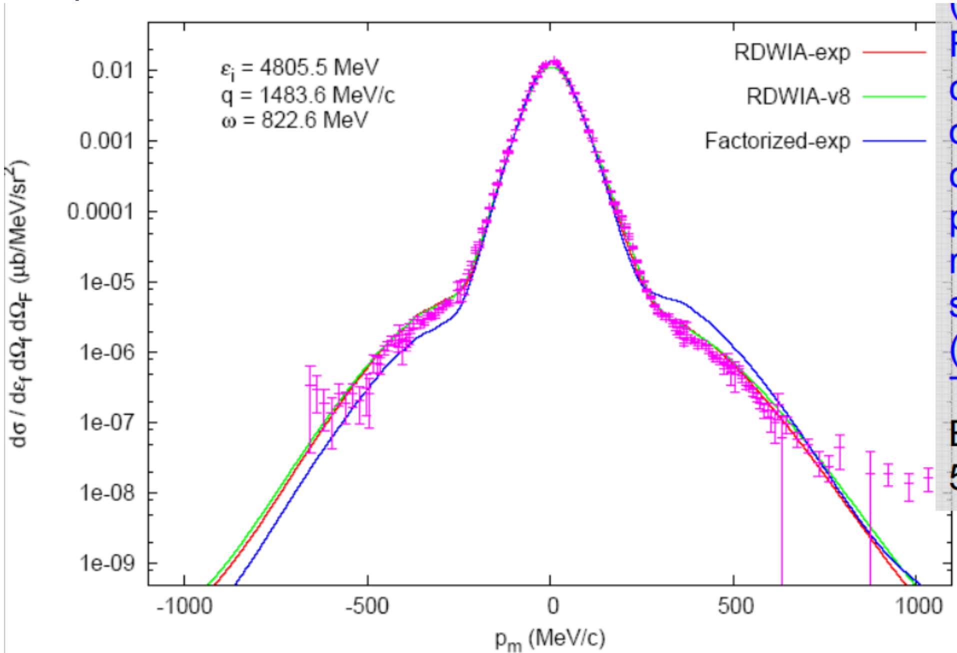
RMF SF "factorisation" approach

- Although RMF does not factorise, this approach mostly works

$$\frac{d^6\sigma}{d\omega d\boldsymbol{q} dE_m d\boldsymbol{p}_m} = KS(E_m, \boldsymbol{p}_m) L_{\mu\nu} H^{\mu\nu} \delta(\omega + M - E_m - E_{p'})$$

- Important: the RMF SF includes the effects of FSI, correlations and the nuclear remnant – **it is not an initial nucleon momentum distribution**
- This approach is **much** easier to implement in an MC than a full 5D xsec, also retains enough control over the physics to add uncertainties
- Our current plan: start with this then compare to full calculation for neutrino relevant scenarios





JM Udias Trento 2019

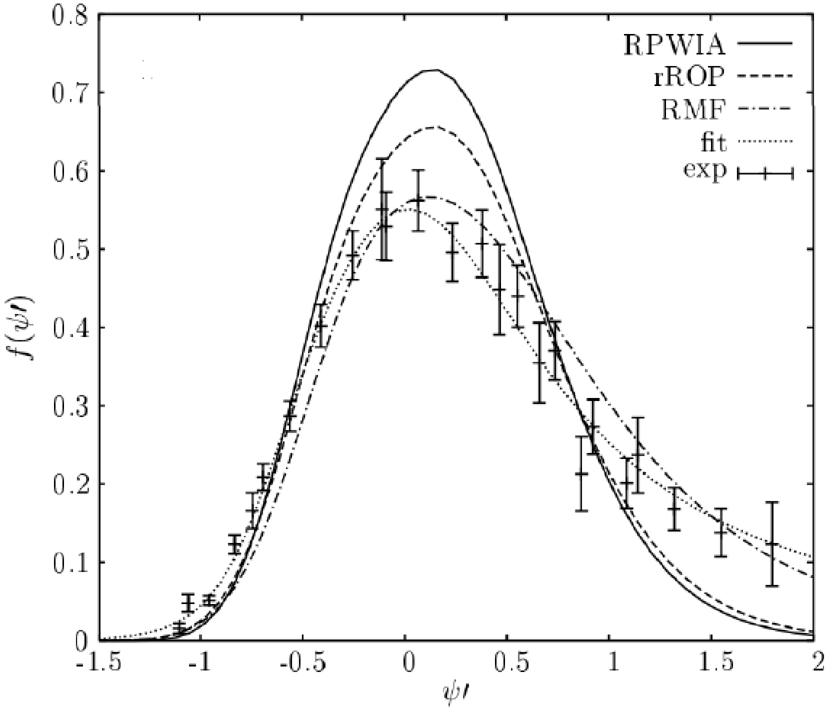
Technical note summary

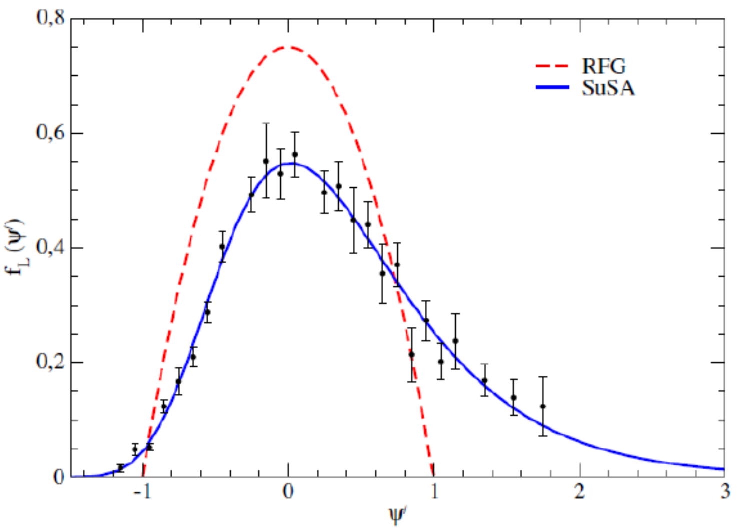
1. Introduction

- DUNE requires neutrino interaction models that can reliably predict the outgoing kinematics of leptons and hadrons from neutrino-Argon scattering
- Current model implementations in the generators are not suitable
- State-of-the-art nuclear models can predict neutrino interactions on all nuclear targets in the same framework with minimal input from A-specific tunes
- Focus on Relativistic Mean Field (RMF) as an example model. Focus mostly on 1p1h (easiest to explain, it's what we have the best models for).

2. 1p1h scattering

- Explain some of the theory behind RMF. Show that it describes "scaling" observed in e,e' data .
- If a model scales well and describes e,e' scaling functions, then it can predict inclusive scattering on any nuclear target.



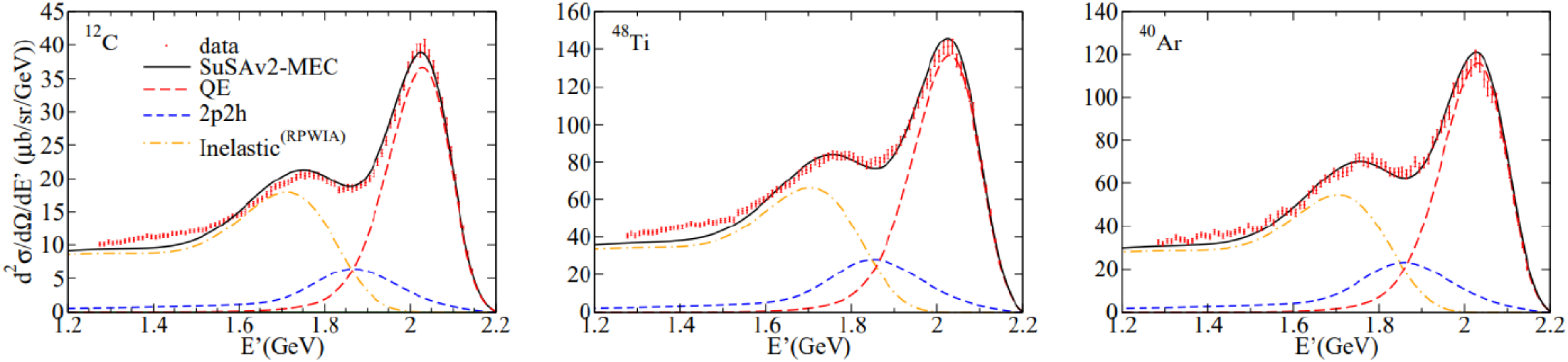


- RMF tells us vector and axial parts scale the same: can extrapolate from e to ν!
- Fermi gas models (as we predominantly use in the generators) do not describe scaling data

2. 1p1h scattering

- RMF requires some modifications to fix overly strong FSI at low q_3, this is done through a "blending function" built from e,e' data on C.

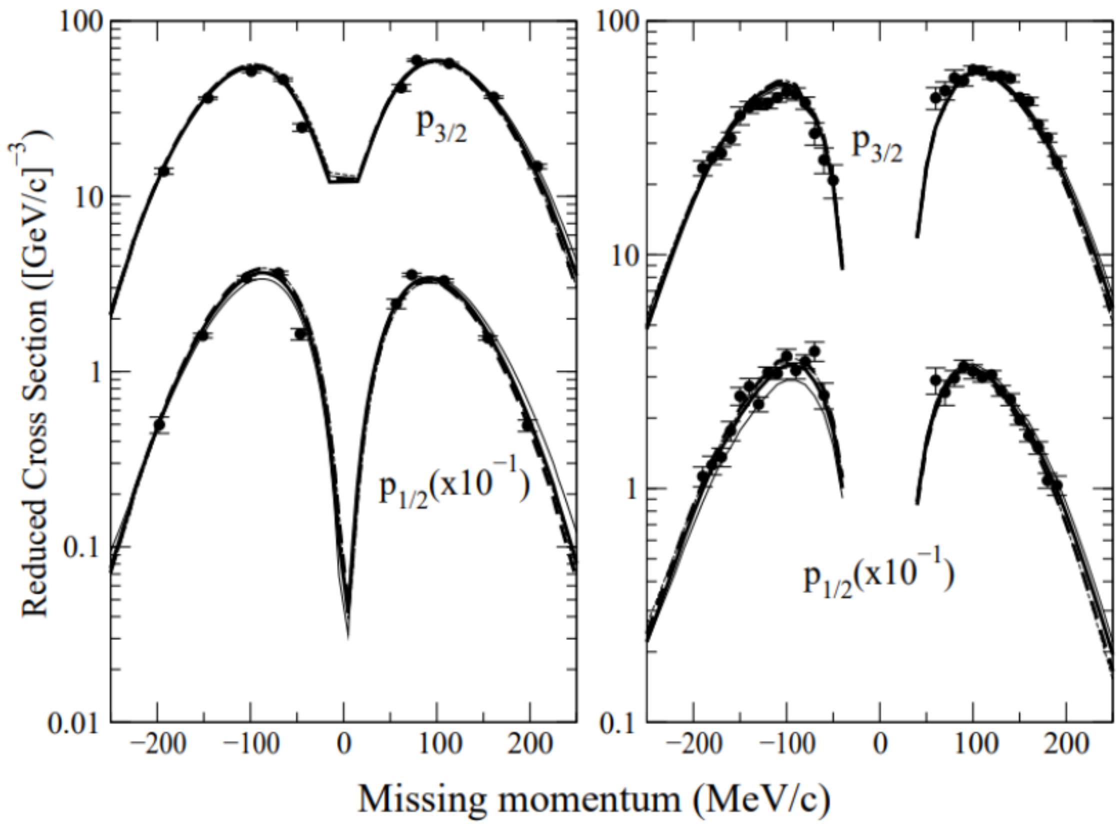
- Apply the modified model to describe the new JLAB data on Ar/Ti:



- It works! Real example of C→Ar extrapolation

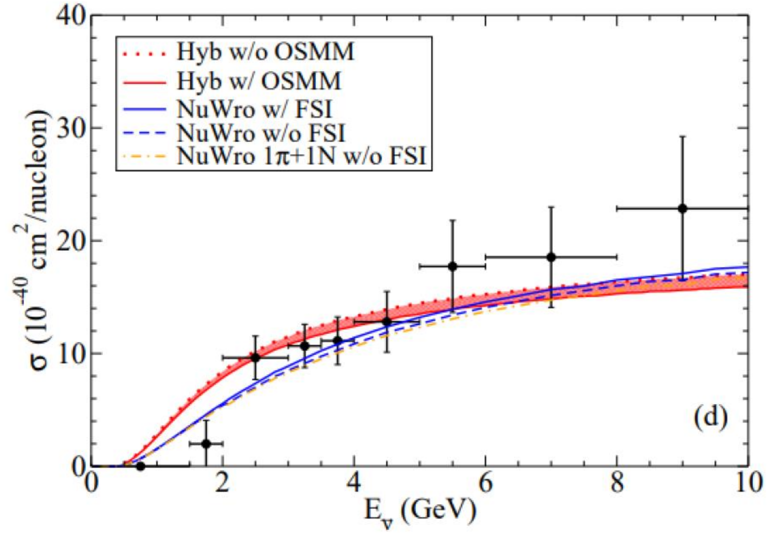
2. 1p1h scattering

- RMF (when equipped with "Relitivistic Optical Potentials" to describe the ejected nucleon) can describe exclusive data. Generators certainly cannot



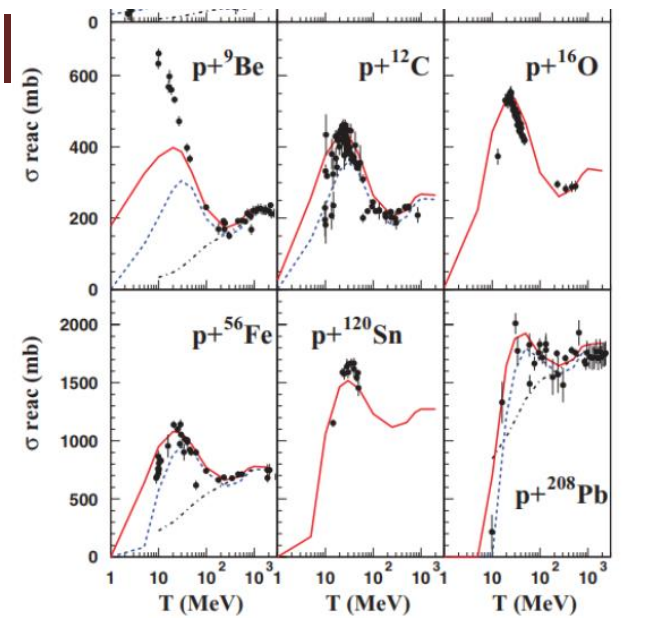
3. Beyond 1p1h

- RMF framework can be applied to pion production. This is a work in progress
- 2p2h in RMF is not easy, but advanced RFG models exist (and have recently been implemented in GENIE) which also exhibit scaling.



4. Nuclear emission from FSI

- Modern microscopic models can predict hadron kinematics, but not additional nuclear emission from FSI.
- Still need a cascade.
- But we can do much better than what we have now, e.g. INCL.



5. Why a CH target?

- Measurement of neutron kinematics
  - Directly measure the largest(?) bias in DUNE's E_{ν}^{rec}
  - $\bar{\nu}H$ extraction using δp_T
- Act as a "lever-arm" w.r.t. Argon data to disentangle different key nuclear effects
- How can we trust a model that can't describe C and Ar to describe ND and FD E_{ν} spectra …

> Overall it can be argued that all that is required for DUNE is a neutrino interaction model that works on Argon, regardless of the agreement on Carbon. However, it is completely unrealistic to expect to have a model which is suitable for a oscillation analysis without proper validation and tuning informed by the near detector and external data. The inclusion of Carbon data in such a tuning is crucial to validate it: if the nominal model used for a DUNE oscillation analysis is unable to describe neutrino interactions on Carbon and Argon in the same framework, it seems reasonable to strongly question the model's ability to extrapolate a model prediction from the near to far detector. After all, as discussed in Sec. 2, the energy dependence and nuclear target dependence of a modern nuclear model stems from the same physics. It is also

6. Conclusions

- Modern models have the physics we need to make Carbon data useful for Argon expeirments
- Carbon becomes a complimentary target, with different enough relative sizes of nuclear effects to help constrain key neutrino interaction systematics
- To do any of this we need these modern models in out generators: essential to support the theorists who can help us do this!